MASSACHUSETTS 1990 GREENHOUSE GAS INVENTORY

Northeast States for Coordinated Air Use Management (NESCAUM)
Massachusetts Executive Office of Environmental Affairs
Massachusetts Division of Energy Resources

December 1996

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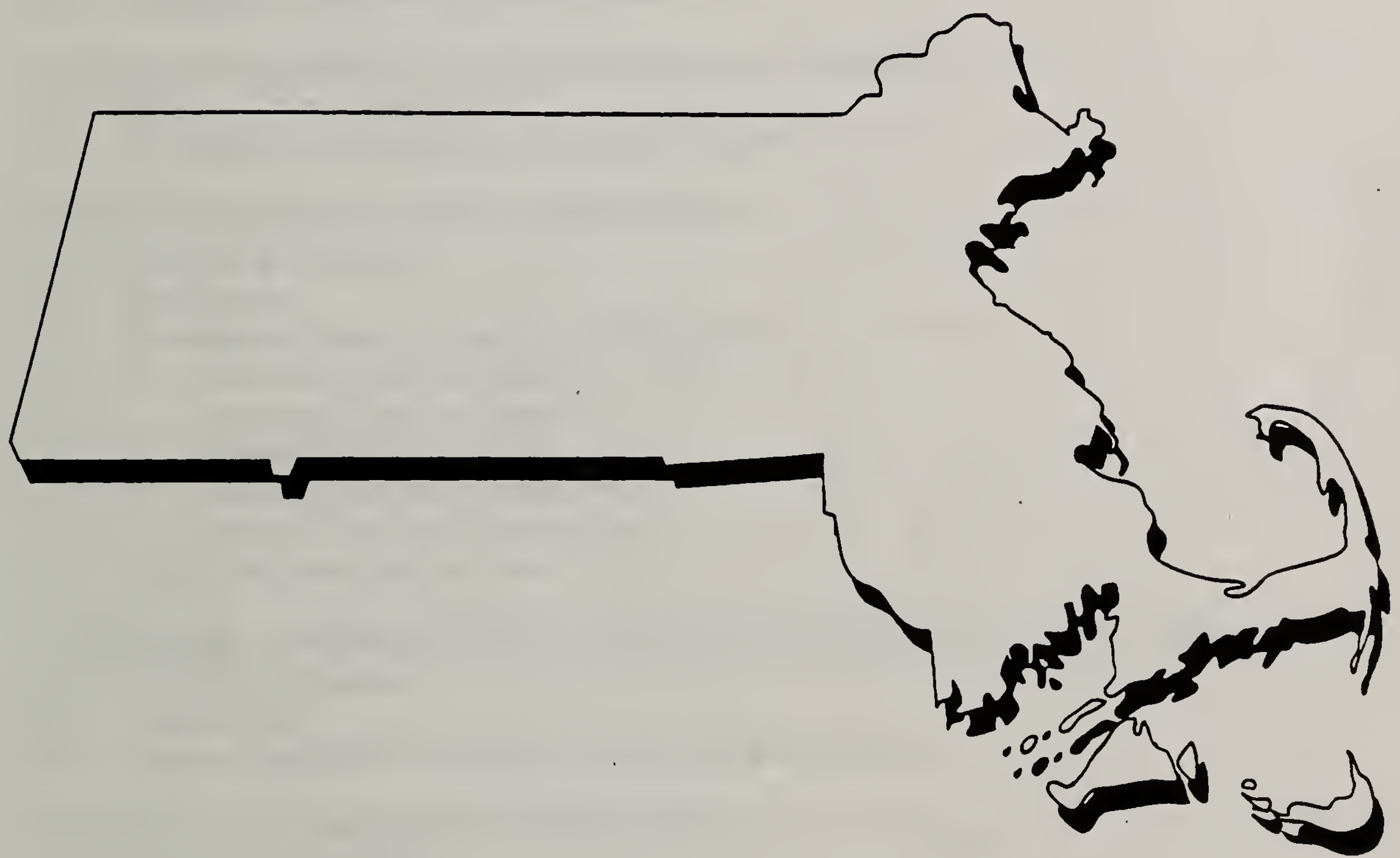

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ACKNOWLEDGMENTS

The *Massachusetts 1990 Greenhouse Gas Inventory* was developed by Northeast States for Coordinated Air Use Management (NESCAUM), the Massachusetts Executive Office of Environmental Affairs (EOEA), and the Massachusetts Division of Energy Resources (DOER), assisted by a grant from the State and Local Climate Change Outreach Program of the U.S. Environmental Protection Agency (EPA). The inventory relies heavily on methodologies developed by the EPA in its *State Workbook, Methodologies for Estimating Greenhouse Gas Emissions* (Second Edition, January 1995).

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The text of this report was written mostly by Marika Tatsutani (NESCAUM); with substantial contributions by Howard Bernstein (DOER), Birgit Caliandro (EOEA), and John Paul Murphy (DOER); and with additional assistance from Vicki Pitluk (DOER) and Joyce Golin (DOER).

EXECUTIVE SUMMARY

A. Background & Context

In recent decades a concern has emerged that the earth's climate is being altered by increased concentrations of certain heat-trapping gases in the atmosphere as a result of human activity. In 1992, the United States joined more than 160 other countries in signing an international convention aimed at achieving the stabilization of greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system."[1] Since 1992, a growing body of scientific analysis and climatological evidence has continued to lend weight to these concerns.

This inventory provides a detailed accounting of greenhouse gas sources and emissions in 1990 for the Commonwealth of Massachusetts.[2] It was undertaken as part of the U.S. Environmental Protection Agency's State and Local Climate Change Outreach Program, which is supporting state efforts to develop information on greenhouse gas sources as the first step to developing state-based options and strategies for reducing emissions. A variety of sources, ranging from fossil fuel combustion to fertilizer use, are covered, as is net carbon sequestration by Massachusetts forests. The main greenhouse gases considered are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).[3] These gases account for approximately 93%, 5%, and 2% of the overall state inventory, respectively.[4] In the summary tables, emissions of these gases are converted to carbon dioxide equivalent tons using conversion factors that reflect their global warming potential relative to carbon dioxide (see further discussion in Section I.B of the Inventory).

B. Inventory Results

The inventory considers only emissions produced within Massachusetts borders, with two exceptions. The inventory also includes estimates of emissions associated with

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1 United Nations, "Report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the Work of the Second Part of Its Fifth Session, Held at New York From 30 April to 9 May, 1992," UN Document A/AC.237/18, Part II (May 15, 1992).

2 The year 1990 was chosen because the goal of current U.S. policy is to return emissions in the year 2000 to 1990 levels as a first step toward stabilizing and eventually reducing greenhouse gas emissions. Twenty-eight other states and Puerto Rico have developed, or are developing, similar inventories with funding and guidance from EPA's State and Local Climate Change Outreach Program.

3 The inventory does not provide estimates of hydrofluorocarbon (HFC) and perfluorocarbon (PFC) emissions, since these are primarily associated with production processes not found in Massachusetts. HFCs and PFCs constitute only 1% of the 1990 national inventory.

4 These percentages are from the bottom line of Table ES-1, which includes emissions from electricity imports and the "upstream fuel cycle," as explained below.

net electricity imports to the state, as well as "upstream" full fuel-cycle emissions associated with extracting, processing, and transporting fossil and nuclear fuels to meet the state's energy demands. These emissions occur out of state but are included because they are directly linked to energy consumption patterns in the state. They are presented separately in order to distinguish them from actual in-state emissions and to avoid double-counting with other states' inventories.

Inventory results are summarized in Tables ES-1 and ES-2. Table ES-1 presents the breakdown of emissions by source category. For this table, emissions associated with electricity consumption (including electricity imports) are apportioned by end-use sector.[5] Overall, energy consumption and other emissions sources in Massachusetts produced about 96.9 million carbon dioxide equivalent tons of greenhouse gas emissions in 1990; adding estimated upstream fuel-cycle emissions brings the state total to 115.6 million tons. Offsetting these emissions, Massachusetts forests are estimated to have absorbed approximately 8.9 million tons of carbon dioxide in 1990. For the United States as a whole, the 1990 inventory was approximately 6,534 million tons of carbon dioxide equivalent emissions, with net biomass sequestration amounting to approximately 497 million tons of carbon dioxide annually.[6]

On the whole, Massachusetts greenhouse gas emissions are lower than the national average relative to population and economic activity. With 2.4% of the U.S. population, the state's 1990 emissions accounted for 1.9% of the 1990 national inventory if one includes upstream fuel-cycle emissions.[7] This works out to annual emissions of 19.2 tons/person in Massachusetts, compared with the national per capita average of 26.3 tons/person in 1990. Relative to economic output, Massachusetts generated 1.78 pounds of carbon dioxide equivalent emissions per dollar of gross state product (GSP) in 1990, again including upstream emissions. This compares to a national average of 2.68 pounds of carbon dioxide equivalent emissions per dollar of gross domestic output in 1990.[8]

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[5] Emissions from fossil fuel combustion to produce electricity for Massachusetts (i.e., including net electricity imports) totaled 28,554,000 tons CO_2; 31,680 CO_2-equivalent tons nitrous oxide; and 13,328 CO_2-equivalent tons methane.

[6] The term "sequestration" refers to the storage of carbon in plant material. National data are from Energy Information Administration (EIA), *Emissions of Greenhouse Gases in the United States 1987-1994*. October, 1995. U.S. Department of Energy. Emissions reported by the EIA in metric tons (tonnes) of carbon were converted to the units used for this inventory, namely short tons of carbon dioxide. See footnotes 10 and 11 in Section II of the Inventory (below) regarding metric and short tons.

[7] *Not* including upstream emissions, Massachusetts' 1990 emissions account for 1.5% of the national inventory, 16.1 tons per person and 1.49 pounds per dollar of gross state product. A case could be made for *not* including upstream emissions, since these are more speculative and may not occur within state or even U.S. borders.

[8] Based on a 1990 Massachusetts gross state product of $129.7 billion (in 1987$) and a 1990 U.S. gross domestic product of $4,877.5 billion (in 1987$). Sources: MA Division of Energy Resources (DOER) and EIA, *1992 Energy Facts*, U.S. Department of Energy, Oct. 29, 1993 (DOE/EIA-0469(92)).

Table ES-1
Breakdown of 1990 Massachusetts Emissions by Source
(thousands of tons of CO_2-equivalent)

	CO_2	CH_4	N_2O	TOTAL
Energy Use*				
Residential	24,034	29	11	24,074
Commercial	21,609	10	840	22,459
Industrial	11,154	6	7	11,167
Transportation	31,436	113	1,374	32,923
Other**	857	0	1	858
Subtotal Energy Use	**89,090**	**158**	**2,233**	**91,481**
Industrial Production Processes	156			156
Landfills	151	4,789		4,940
Agriculture		197	11	208
Municipal Wastewater		120		120
TOTAL All Sources (without Upstream)	**89,397**	**5,264**	**2,244**	**96,905**
Upstream Fuel Cycle***	18,727			18,727
TOTAL (with Upstream)	**108,124**	**5,264**	**2,244**	**115,632**

* Emissions from electricity production (including net electricity imports) are distributed among end-use sectors based on their share of demand (see Section III for further discussion). Emissions from wood and municipal solid waste combustion are not included (as explained in Section III.B).

** Electricity-related emissions that could not be assigned to a particular end-use sector. May include line losses and other unaccounted-for electricity uses.

*** Upstream fuel cycle emissions are emissions associated with the extraction, processing, and transportation of fuels used to meet the state's energy needs. Although some are generated in-state, the upstream fuel cycle emissions are largely generated in other, energy-producing states and, to some extent, may occur outside the U.S. altogether. See Section IV for further discussion.

Though low relative to the national average, Massachusetts greenhouse gas emissions are high by world standards. In 1989, the median global per capita emissions rate was just 3.3 carbon dioxide equivalent tons per person, a fraction of per capita emissions in Massachusetts.[9] Even compared to similarly industrialized countries like Japan and Germany, the state -- like the nation as a whole -- uses more energy and generates higher emissions per capita.[10]

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[9] World Resources Institute (in collaboration with the United Nations Environment Programme and the United Nations Development Programme), *World Resources 1992-93*. Oxford University Press, 1992, p. 209. Note that the World Resources figures, given in metric tons (tonnes), were converted to short tons for purposes of this comparison. Note also that the World Resources data were for 1989. This was judged to be sufficiently close to 1990 for purposes of this comparison.

[10] Per capita U.S. carbon dioxide emissions from fossil fuel burning were more than double those of Japan and 80% higher than those of Germany in 1994. *Source:* Lester Brown, et. al. *State of the World 1996*. Worldwatch Institute, 1996. Table 2-2, p. 30.

Table ES-2 presents the balance of carbon flows from wood combustion, land use change (primarily deforestation), and biomass regeneration. These figures should be regarded as approximate, since this sector is characterized by relatively poor data, significant uncertainties and necessary simplifications in the calculation methodology. Overall, Massachusetts forests absorb more carbon dioxide than is released by forest harvesting, fuelwood combustion, and forest conversion to other land-uses. However, carbon sequestration by forests offsets less than 8% of the total emissions inventory (including emissions from electricity imports and the upstream fuel cycle).

Table ES-2
Approximate Annual Biomass-Related Carbon Flux*

	Annual Carbon Emissions (tons)	Annual CO_2 Emissions (000 tons)
Fuelwood Combustion	123,280	452
Forest Harvesting	136,400	500
Land Use Change	646,050	2,369
Forest Sequestration	-3,321,000	-12,177
Urban Tree Planting	-158	-1
TOTAL	**-2,415,428**	**-8,857**

* The negative numbers signify CO_2 *removed* from the atmosphere.

Table ES-3 shows that energy related emissions play a larger role in the state inventory than they do in the national inventory, reflecting the lesser importance of agricultural and industrial process sources in the state's economy.[11] The most striking difference between the state and national figures is the relative importance of the industrial sector.[12] Nationwide, the industrial sector contributes the largest share of energy-related carbon dioxide emissions. In Massachusetts, by contrast, it is the least significant energy end-use sector. Instead, transportation is the largest single end-use sector for energy-related greenhouse gas emissions in the state, and the residential and commercial sectors assume a proportionately larger role than is typical nationwide.

[11] Note that these comparative figures may be slightly skewed by the fact that this Massachusetts inventory does not include halocarbons and related compounds, and by the fact that a figure for U.S. methane emissions associated with municipal wastewater was not included in the national inventory data. Source for all U.S. data: EIA, 1995, *Ibid.*

[12] Note here that electric utilities are not included in the industrial sector. Though utilities are significant *primary* energy users, they are not considered an *end-use* sector. For further discussion of the distinction between primary and end-use energy consumption, see Footnote 20 in Section III.A of the Inventory.

Table ES-3
1990 Greenhouse Gas Sources: Massachusetts vs. U.S.
(as % of total inventory)*

	MA	U.S.
Residential Energy Use	25%	17%
Commercial Energy Use	23%	13%
Industrial Energy Use	12%	30%
Transportation Energy Use	34%	28%
SUBTOTAL ENERGY USE**	**94%**	**88%**
Landfills	5%	5%
Industrial Production Processes	<1%	2%
Agriculture	<1%	4%
HFCs & PFCs	?	1%
Municipal Wastewater	<1%	?
TOTAL ALL SOURCES	**100%**	**100%**

* Note that slightly different percentages can be obtained depending on how upstream fuel cycle emissions, non end-use sector energy consumption, and other differences between the Massachusetts and U.S. inventories are handled.

** In this table, emissions associated with electricity production (including electricity imports) have been apportioned to end-use sectors based on their share of total electricity demand. Emissions associated with the upstream fuel cycle have not been included in this table.

C. Projected Trends in Carbon Dioxide Emissions

To provide some indication of future emissions trends, carbon dioxide emissions associated with state projections for year 2000 fossil fuel consumption were estimated. While this approach does not provide a complete picture of future greenhouse gas emissions (since non-energy and non-carbon dioxide emissions were not considered), energy-related carbon dioxide emissions are expected to continue to dominate the state's overall inventory into the future.

Table ES-4 shows the estimated 1990 carbon dioxide emissions, along with the projected emissions in the year 2000 and the percentage of increase in each sector of primary fuel use. Figure ES-1 shows the relative contributions made by each sector to the total projected increase (from the Projected Increase column of Table ES-4). Figure ES-2 shows the trend line in carbon dioxide emissions between 1990 and the year 2000 for the primary energy use sectors (but with year-to-year changes not shown).

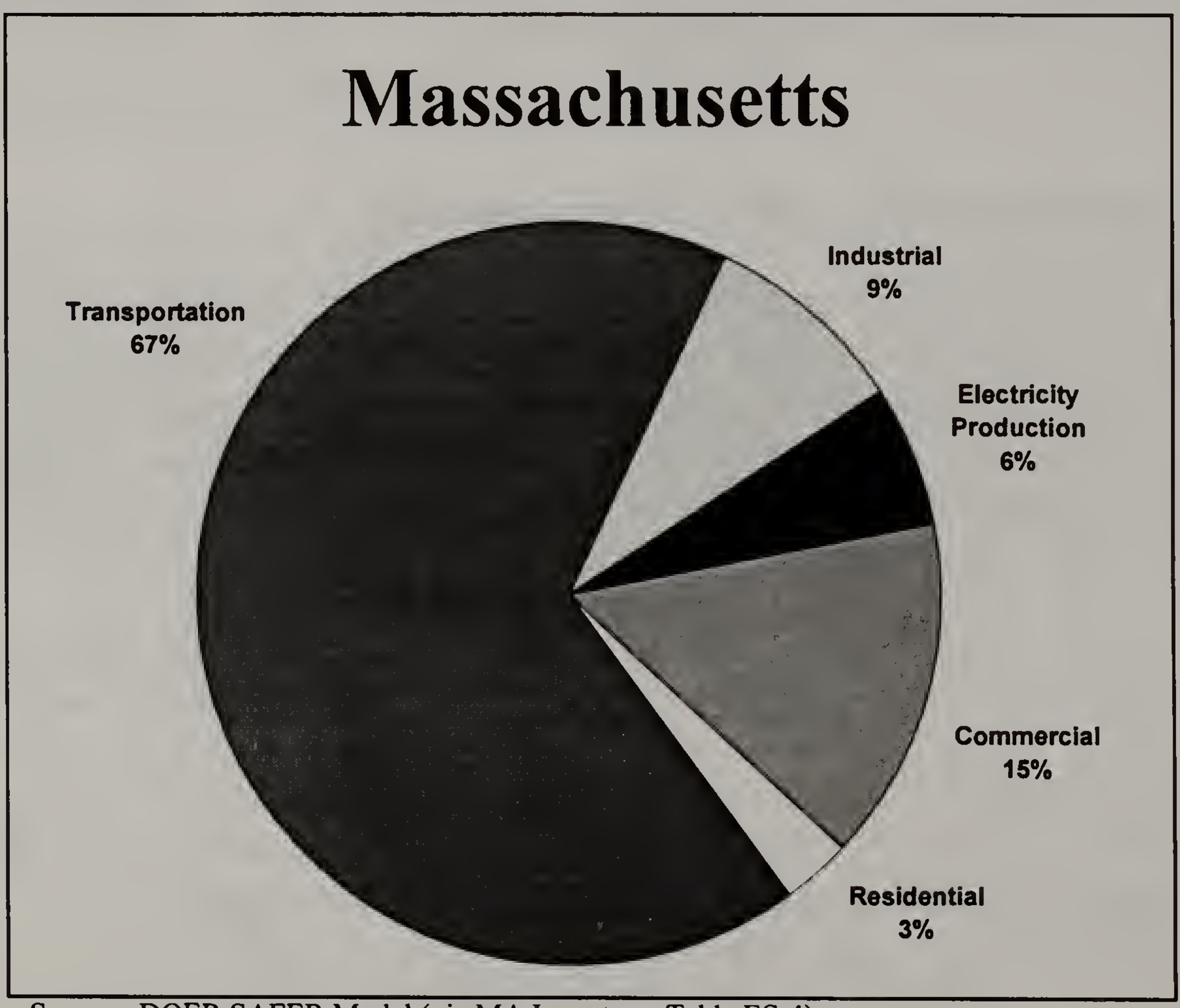
Table ES-4
Projected Year 2000 CO_2 Emissions from Primary Energy Use*
(in thousands of tons)

	1990 Emissions (actual)	**2000 Emissions** (projected)	**Projected Increase, 1990-2000**	**Percentage Change, 1990-2000**
Residential	14,326	14,659	333	+ 2.3%
Commercial	9,902	11,343	1,441	+14.6%
Industrial	4,872	5,750	878	+18.0%
Transportation	31,436	38,076	6,640	+21.1%
Electricity Production**	28,554	29,192	638	+ 2.2%
TOTAL	**89,090**	**99,020**	**9,930**	**+11.1%**

* Does not include emissions from wood combustion or upstream fuel-cycle emissions. Projected electricity emissions are not apportioned by end-use sector.

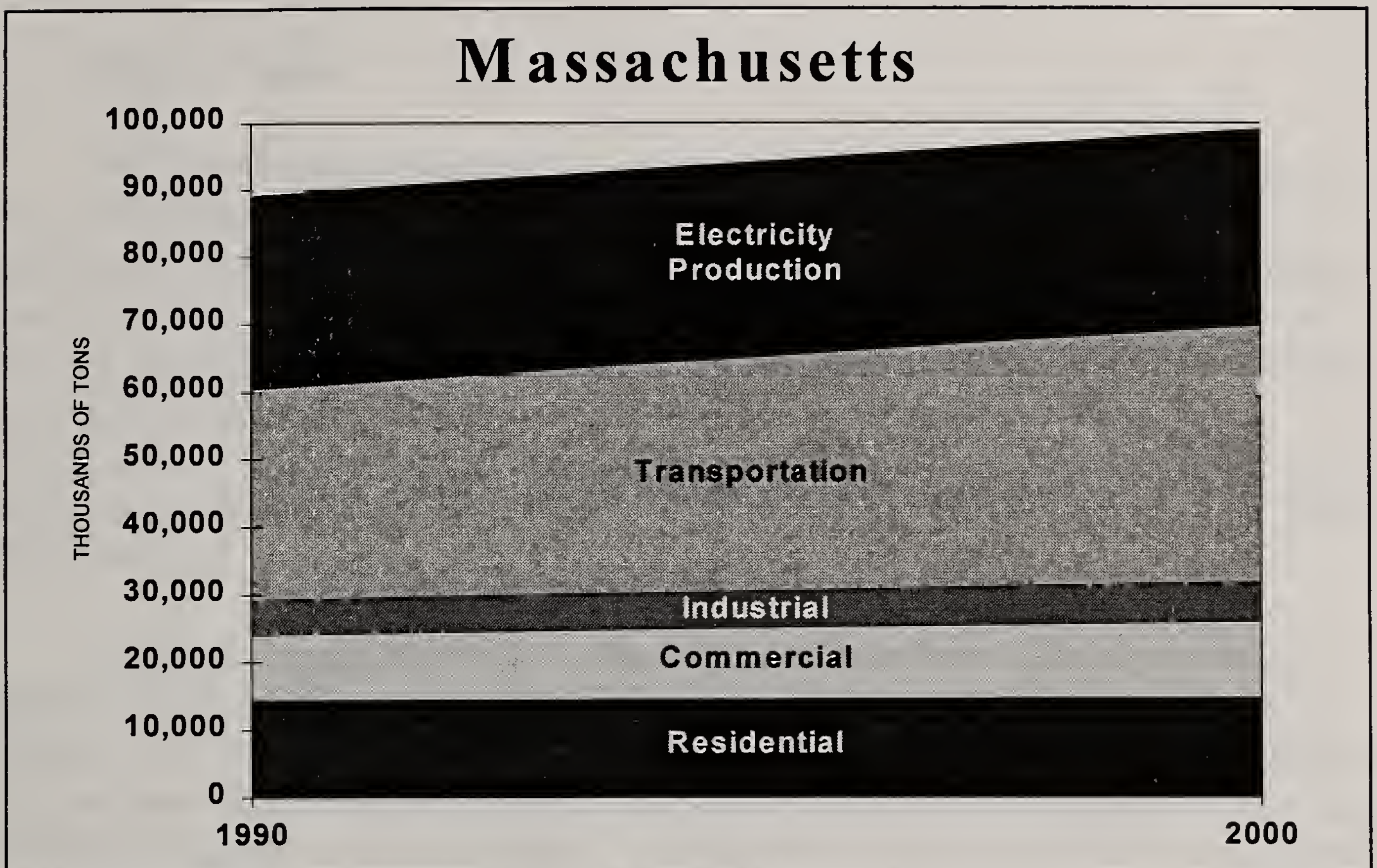
** Electricity Production includes net electricity imports.

Figure ES-1
Shares of Total Projected CO_2 Emissions Increase, 1990-2000



Source: DOER SAFER Model (via MA Inventory, Table ES-4).

Figure ES-2
1990-2000 Projected CO_2 Emissions from Primary Energy Consumption*



Source: DOER SAFER Model (via MA Inventory, Table ES-4)
* It should be noted that year-to-year fluctuations are not indicated on this graph.

Overall, energy-related carbon dioxide emissions are projected to grow by 11.1% in the 1990-2000 period.[13] By far the greatest growth, in both absolute and percentage terms, is projected to occur in the transportation sector, which is expected to contribute about two-thirds of the increased emissions in 2000 (see Figure ES-1). However, commercial and industrial sector emissions are also expected to grow significantly. Fuel switching -- to natural gas in the residential sector and to natural gas and hydropower in the electricity production sector -- results in somewhat decreased use of fuel oil and coal, helping to dampen projected carbon dioxide emissions increases in these sectors.

In order to return year 2000 emissions to 1990 levels, Massachusetts would need to reduce projected emissions by approximately 10 million tons of carbon dioxide equivalent.

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[13] Projections were generated using DOER's State Annual Forecast of Energy Resources (SAFER) model. The SAFER model is described in Appendix A.

I. BACKGROUND & INTRODUCTION

A. Global Climate

With better understanding of the environmental impacts of human activities, it has become increasingly clear that the Earth's biosphere depends on a dynamic set of interrelated systems. Humans and other species have adapted to climatic conditions that depend on a complicated balance between the amount of solar energy that enters and leaves the atmosphere. In recent decades, a concern has emerged that human activities may be interfering with this balance. Scientists have postulated that increasing concentrations of certain gases in the atmosphere could lead to changes in global climate patterns, a phenomenon that has become widely known as "global warming," or "global climate change."

Conditions hospitable to life on Earth have always depended on an existing, naturally occurring phenomenon that is often described as the "greenhouse effect." Incoming solar radiation is absorbed by the atmosphere and the Earth's surface. Some of it is re-radiated back from the surface as long-wave radiation, and trapped by water vapor and other trace gases in the atmosphere. Because these gases allow solar energy to enter the atmosphere, but prevent some of it from leaving, they create a heat-trapping effect similar to what happens in a glass enclosed greenhouse. Without this effect, the Earth's average temperature would be about -16° C (-60° F), and climate conditions on the planet would be much closer to those that prevail on Mars.[1]

A number of gases can absorb the Earth's re-radiated heat and contribute to the greenhouse effect. These include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and certain halocarbons and related compounds (such as CFC-11 and CFC-12). All of these gases, except halocarbons, occur naturally. With the exception of water vapor, which makes up approximately one percent of the earth's atmosphere, the greenhouse gases exist only in trace amounts in the atmosphere. The most abundant, carbon dioxide, constitutes less than 0.04 percent of the atmosphere. Nevertheless, these gases play a crucial role in determining climatic conditions on the planet.

Atmospheric measurements and analysis of air trapped in polar ice cores reveal that atmospheric concentrations of a number of these gases are increasing. For instance, measured concentrations of carbon dioxide in the atmosphere have increased from pre-industrial levels of 278 parts per million (ppm) to 356 ppm in 1990. Methane has increased from 0.7 ppm to 1.7 ppm over the same period. The coincidence of these upward trends, with the onset of the Industrial Age approximately 200 years ago, strongly

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[1] Presently, the Earth's average surface temperature is about 15°C (59°F). Source: Donald Ahrens, *Meteorology Today: An Introduction to Weather, Climate, and the Environment*, 1994. p. 2.

suggests that human activities are contributing to observed changes in greenhouse gas concentrations. Scientists have attempted to gauge the impacts of these changes on the global climate system with sophisticated computer models. The most recent assessment of the International Panel for Climate Change (IPCC), an international team of meteorologists and climate scientists convened under the auspices of the United Nations, states:

> Human activities are increasing the atmospheric concentrations of greenhouse gases - which tend to warm the atmosphere - and, in some regions, aerosols - which tend to cool the atmosphere. These changes in greenhouse gases and aerosols, taken together, are projected to lead to regional and global changes in climate and climate-related parameters such as temperature, precipitation, soil moisture and sea level. Based on the range of sensitivities of climate to increases in greenhouse gas concentrations reported by IPCC Working Group I and plausible ranges of emissions, . . . climate models, taking into account greenhouse gases and aerosols, project an increase in global mean surface temperature of about 1-3.5° C [1.8-6.3° F] by 2100, and an associated increase in sea level of about 15-95 centimeters [5.9-37.1 inches].[2]

Though climate change predictions remain fraught with uncertainties, scientists have pointed out that even small changes in mean global temperatures could have significant impacts. By way of example, average global temperatures during the last major ice age about 11,000 years ago were only about 3° C (5.4° F) lower than at present. Over subsequent millennia, average global temperatures have varied no more than 1.5° C (2.7° F).[3] Moreover, the *rate* of climate change, as much as its eventual magnitude, may be critical to the ability of human and natural systems to adapt. According to the IPCC:

> The reliability of regional-scale predictions is still low, and the degree to which climate variability may change is uncertain. However, potentially serious changes have been identified, including an increase in some regions in the incidence of extreme high temperature events, floods, and droughts, with resultant consequences for fires, pest outbreaks, and ecosystem composition, structure, and functioning, including primary productivity.[4]

In addition to impacts on ecosystems and agricultural productivity, scientists have theorized that global climate change could have potentially devastating consequences in terms of sea level rise and the increased incidence and severity of major storms and other extreme weather events. A series of particularly damaging and costly hurricanes, cyclones, and typhoons, which led to unprecedented property losses in the last several years, has recently prompted the global insurance industry to pay increased

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[2] Intergovernmental Panel on Climate Change (IPCC), from the "Summary for Policymakers: Scientific Technical Analysis of Impacts, Adaptations, and Mitigation of Climate Change", IPCC Working Group II, 1995. (Note: conversions to degrees Fahrenheit and inches do not appear in the original text.)

[3] Donald Ahrens, *op cit.*, pp. 481-482.

[4] IPCC, 1995, *op cit.*

attention to the issue of climate change. In 1992, international awareness of the many potential risks associated with global warming led to the adoption by more than 160 countries, including the United States, of an International Framework Convention on Climate Change. The stated objective of this Convention, often referred to as the "Rio Treaty," was to:

> . . . achieve . . . stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.[5]

Toward this objective, signatories pledged to work to stabilize greenhouse gas emissions. A number of industrialized countries, including the United States, adopted the specific near-term goal of returning year 2000 greenhouse gas emissions to 1990 levels. Since then, it has become evident that most countries, including the United States, are not on track to meet this objective. In March 1995 at the Berlin Conference of the Parties to the Framework Convention on Climate Change, diplomats opened a new round of negotiations intended to lead to further emission reduction commitments by 1997. In addition, governments agreed to consider further actions to mitigate climate risks and to promote the transfer of less carbon intensive technologies between countries.

B. Greenhouse Gases and "Global Warming Potential" (GWP)

As noted previously, there are a number of gases in the atmosphere that have a heat trapping effect. The heat trapping properties of these gases vary. In order to clarify their relative importance, the concept of "global warming potential" (GWP) has been developed. Using carbon dioxide as the standard, researchers have assigned a GWP index number to each greenhouse gas, which gives its estimated climate impact, over a specified time period, expressed as an equivalent release, by weight, of carbon dioxide.[6] For instance, the 100-year GWP for methane is 24.5, which means that one ton of methane emissions is estimated to have the same warming impact, over 100 years, as 24.5 tons of carbon dioxide emissions. Similarly, the 100-year GWP for nitrous oxide is 320, which means that one ton of nitrous oxide emissions has the same effect over 100 years as 320 tons of carbon dioxide.[7]

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[5] United Nations, "Report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the Work of the Second Part of Its Fifth Session, Held at New York From 30 April to 9 May, 1992," UN Document A/AC.237/18, Part II (May 15, 1992).

[6] Global Warming Potential is quite sensitive to the time period over which radiative effects are measured. For example, the 20-year GWPs for methane and nitrous oxide are 62 and 290 respectively. The 100-year GWP is used throughout this inventory for consistency with the EPA *Workbook* and with most national and international assessments.

[7] In 1995, the IPCC issued a revised set of GWPs (Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1994: Radiative Forcing of Climate Change*, Cambridge University Press, 1995). The revised 100-year GWP for methane is 24.5, compared to the earlier figure of 22, and the revised 100-year GWP for nitrous oxide is 320, compared to 270. Throughout this inventory, the GWPs published by the

The most important greenhouse gas is water vapor. However, water vapor is not emitted directly by human activities in quantities that are significant relative to natural sources. The greenhouse gas of greatest concern from the standpoint of anthropogenic emissions is carbon dioxide. Carbon dioxide is a natural by-product of the oxidation of carbon in organic matter, either through the combustion of carbon-based fuels or the decay of biomass. Thus, the chief anthropogenic sources of carbon dioxide are fossil fuel combustion and deforestation. It is estimated that carbon dioxide is responsible for 85% of total U.S. greenhouse gas emissions.

The second most important anthropogenic greenhouse gas is methane. which -- converted to carbon dioxide equivalent terms based on its GWP -- constitutes 12% of the national greenhouse gas emissions inventory. Methane is primarily produced by anaerobic decay of organic material in landfills, rice fields and natural wetlands, and by the digestive tracts of ruminant domestic animals (most notably cattle, sheep, and goats). Nitrous oxide constitutes approximately 2% of the national inventory, on a carbon dioxide equivalent basis, and is primarily produced by fertilizer use, combustion of fuels, and certain industrial processes. The chief halocarbons -- hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) -- make up another 1% of the national inventory.

C. The Massachusetts 1990 Inventory Project

Climate change is a serious environmental concern to Massachusetts, given the potential impact on shorelines, coastal wetlands and other habitat, as well as on crops, wildlife, and human health and safety. As part of a United States initiative to reduce greenhouse gas emissions, a number of states are examining their individual contributions to the national inventory and are exploring policy options for state actions to mitigate the risks of potential climate change. Twenty-eight other states and Puerto Rico have developed, or are developing, similar inventories under EPA's State and Local Climate Change Outreach Program. This inventory of 1990 Massachusetts greenhouse gas emissions is the Commonwealth's first step toward developing such options.

This inventory was developed by Northeast States for Coordinated Air Use Management (NESCAUM), the Massachusetts Executive Office of Environmental Affairs (EOEA), and the Massachusetts Division of Energy Resources (DOER) with a grant from the U.S. Environmental Protection Agency (EPA). The methodology was taken from EPA's *State Workbook, Methodologies for Estimating Greenhouse Gas Emissions* (Second Edition, January 1995), hereinafter referred to as the *Workbook.* The *Workbook* was used to identify likely greenhouse gas sources and to calculate their emissions, as described in the following sections.

IPCC in 1995 are used in place of the GWPs published in EPA's *State Workbook, Methodologies for Estimating Greenhouse Gas Emissions*, Second Edition, to convert emissions of greenhouse gases to carbon dioxide equivalents.

With the 1990 inventory as a baseline, the Commonwealth intends to identify and analyze potential strategies and policy options for reducing state emissions of greenhouse gases while simultaneously producing other useful social ends.

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II. 1990 MASSACHUSETTS GREENHOUSE GAS EMISSIONS

A. Summary of Inventory Results

This inventory presents estimated 1990 emissions from all major sources of greenhouse gas emissions in the Commonwealth of Massachusetts. The year 1990 was chosen because the goal of current United States policy is to return year 2000 greenhouse gas emissions to 1990 levels as a first step toward stabilizing and eventually reducing emissions. Sources considered include fossil and biomass fuel combustion, industrial production processes, fossil fuel production systems ("upstream" emissions), landfills, agricultural sources (including domestic animals, manure and soil management), forest management and land-use changes, and municipal waste water.

With two significant exceptions, the inventory accounts only for emissions produced within Massachusetts' borders. The exceptions are emissions associated with electricity imports to the state and "upstream" full fuel-cycle emissions associated with the extraction, processing, and transportation of fossil and nuclear fuels that are ultimately consumed to meet the state's energy demands. Emissions from these sources were calculated because they are directly associated with in-state energy demand. However, the results are presented separately, in order to distinguish them from emissions that occur within state borders and to avoid double-counting problems with other states' inventories. The inventory does not attempt to quantify out-of-state emissions associated with other products or services consumed within Massachusetts.[8]

The inventory results are summarized in Tables II-1 and II-2. The only major class of greenhouse gases for which Massachusetts estimates are not provided are the hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). The EPA *Workbook* provides calculation methodologies for HFC and PFC emissions only in connection with aluminum and chemical production processes, neither of which are found in Massachusetts. This class of greenhouse gases constitutes only 1% of the 1990 national emissions inventory, on a carbon dioxide equivalent basis, so that any HFC and PFC emissions that do occur in Massachusetts can be assumed to constitute a very minor portion of the overall state inventory.

Table II-2 breaks down the major sources of greenhouse gas emissions in Massachusetts. Emissions associated with electricity consumption (both electricity generated within the state and electricity imports) are apportioned by end-use category. In 1990, emissions from electricity production totaled 28,599 thousand tons of carbon

[8] Such an analysis, which would have to account for the upstream emissions associated with products and services *exported from* Massachusetts, as well as with products and services *imported to* the state, is beyond the scope of this exercise.

dioxide equivalent, approximately 30% of the total state inventory.[9] Table II-2 also includes "upstream fuel cycle" emissions associated with the extraction, processing, and transportation of fuels used to meet the state's energy needs.

Table II-1
1990 Massachusetts Greenhouse Gas Emissions, All Sources[10]

		Emissions (1000 tons)	CO_2-Equivalent (1000 tons)
IN-STATE:	**CO_2**	88,313	88,313
	CH_4	215	5,264
	N_2O	7	2,243
In-State Subtotal			**95,820**
OUT-OF-STATE:			
Net Electricity Imports	**CO_2**	1,084	1,084
Upstream Fuel Cycle*	**CO_2-equivalent**		18,727
Out-of-State Subtotal			**19,811**
TOTAL			**115,631**

* Upstream fuel cycle emissions are those associated with the extraction, processing, and transportation of fuels used to meet the state's energy needs. Although some are generated in-state, the upstream fuel cycle emissions are largely generated in other, energy-producing states and, to some extent, may occur outside the U.S. altogether. See further discussion in Section IV.

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9 The breakdown of 1990 emissions from electricity production (including net electricity imports) was 28,554,000 tons CO_2; 31,680 CO_2-equivalent tons N_2O; and 13,328 CO_2-equivalent tons CH_4. (See Sections III.C.5 and III.D)

10 Throughout this inventory, quantities of greenhouse gases are expressed in short tons, as opposed to metric tons (tonnes). (One short ton equals 2,000 pounds. In international discussions, greenhouse gas emissions are more commonly expressed in metric tonnes. One metric tonne equals 1.1023 short tons.) The tables generally show actual emissions of the relevant greenhouse gas(es), together with emissions converted to carbon dioxide equivalents using published global warming potentials (see discussion in pages 3 and 4). To convert carbon emissions to carbon dioxide emissions, tons of carbon are multiplied by the molecular weight ratio of carbon dioxide to carbon (i.e., 44/12 or 3.667). Thus one ton of carbon emissions yields 3.667 tons of carbon dioxide emissions. While emissions are calculated down to tons (and in a few cases, fractions of tons), the key metric used throughout this inventory and found in the last column of almost all the tables is ***thousands*** *of tons of carbon dioxide* (CO_2) *equivalent.* Final results are expressed in thousands of tons both for ease in handling large aggregate sums and to avoid presenting results with a degree of precision that would be misleading, given numerous uncertainties in the source data and the calculation methodology.

Table II-2
Breakdown of 1990 Massachusetts Emissions by Source
(thousands of tons of CO_2-equivalent)

	CO_2	CH_4	N_2O	TOTAL
Energy Use*				
Residential	24,034	29	11	24,074
Commercial	21,609	10	840	22,459
Industrial	11,154	6	7	11,167
Transportation	31,436	113	1,374	32,923
Other**	857	0	1	858
Subtotal Energy Use	**89,090**	**158**	**2,233**	**91,481**
Industrial Production Processes	156			156
Landfills	151	4,789		4,940
Agriculture		197	11	208
Municipal Wastewater		120		120
TOTAL All Sources (without Upstream)	**89,397**	**5,264**	**2,244**	**96,905**
Upstream Fuel Cycle***	18,727			18,727
TOTAL (with Upstream)	**108,124**	**5,264**	**2,244**	**115,632**

* Emissions from electricity production (including net electricity imports) are distributed among end-use sectors based on their share of demand (see Section III for further discussion). Emissions from wood and municipal solid waste combustion are not included (as explained in Section III.B).

** Electricity-related emissions that could not be assigned to a particular end-use sector. May include line losses and other unaccounted-for electricity uses.

*** Upstream fuel cycle emissions are emissions associated with the extraction, processing, and transportation of fuels used to meet the state's energy needs. Although some are generated in-state, the upstream fuel cycle emissions are largely generated in other, energy-producing states and, to some extent, may occur outside the U.S. altogether. See Section IV for further discussion.

Table II-3 presents the balance of carbon flows from wood combustion, land use change (primarily deforestation), and biomass regeneration. These figures should be regarded as approximate, since this sector is characterized by poor data, and since significant uncertainties and simplifications were made in the calculation methodology (see Section IX). Overall, Massachusetts forests absorb more carbon dioxide than is released by forest harvesting, fuelwood combustion, and forest conversion to other land-uses. However, carbon sequestration by forests offsets less than 8% of the total emissions inventory (including emissions from electricity imports and the upstream fuel cycle).

Table II-3
Approximate Annual Biomass-Related Carbon Flux*

	Annual Carbon Emissions (tons)	Annual CO_2 Emissions (000 tons)
Fuelwood Combustion	123,280	452
Forest Harvesting	136,400	500
Land Use Change	646,050	2,369
Forest Sequestration	-3,321,000	-12,177
Urban Tree Planting	-158	-1
TOTAL	**-2,415,428**	**-8,857**

* The negative numbers signify CO_2 *removed* from the atmosphere.

B. Comparison of Massachusetts Inventory to National Inventory

Overall, carbon dioxide emissions account for more than 92% of the state's total emissions inventory in 1990, methane emissions for more than 5%, and nitrous oxide emissions for more than 2% -- on a carbon dioxide equivalent basis (in-state emissions only). This breakdown is compared to the breakdown for the national inventory in Figure II-1. Methane emissions clearly make a smaller contribution to the overall Massachusetts greenhouse gas inventory than to the national inventory. This is consistent with the fact that many of the chief sources of methane emissions nationally (including agriculture, rice fields, coal mines, and energy production systems) do not play a major role in the state.

It is also interesting to compare Massachusetts to the nation as a whole in terms of 1990 greenhouse gas emissions relative to population and economic activity. Not including upstream fuel-cycle emissions, the state's 1990 inventory of 96.9 million tons of carbon dioxide equivalent emissions accounted for approximately 1.5% of the national inventory of 6,534 million tons.[11] By comparison, the state's 1990 population, at 6.02 million people, represented approximately 2.4% of the national population. Thus, Massachusetts' average per capita emissions -- at 16.1 tons/person in 1990 -- were substantially lower than the national average of 26.3 tons/person. Adding in the estimate for upstream fuel-cycle emissions associated with fuels used to meet Massachusetts energy demand increases the state inventory to 115.6 million tons, or 1.8% of the 1990 national inventory, and raises per capita emissions to 19.2 tons/person -- still well below the national average.

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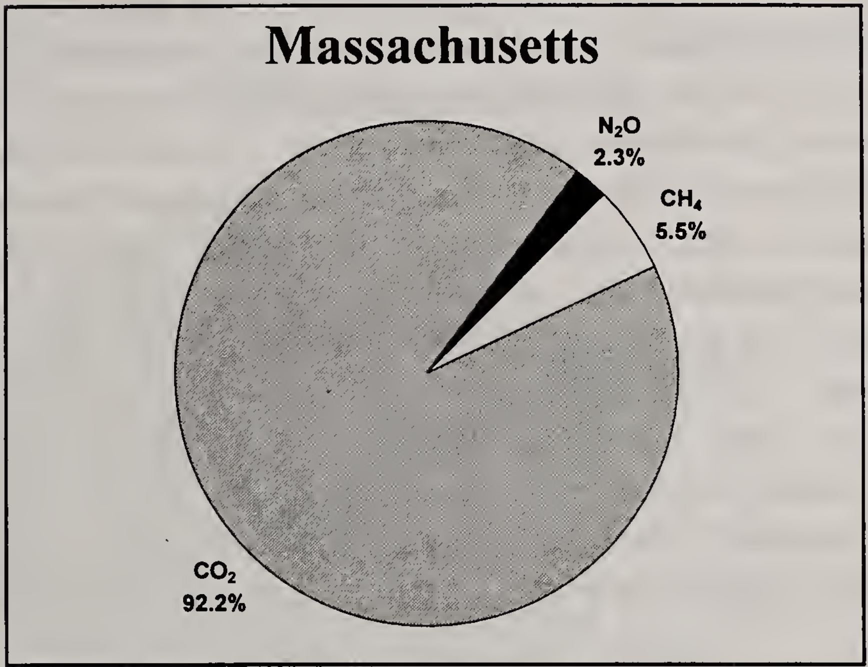
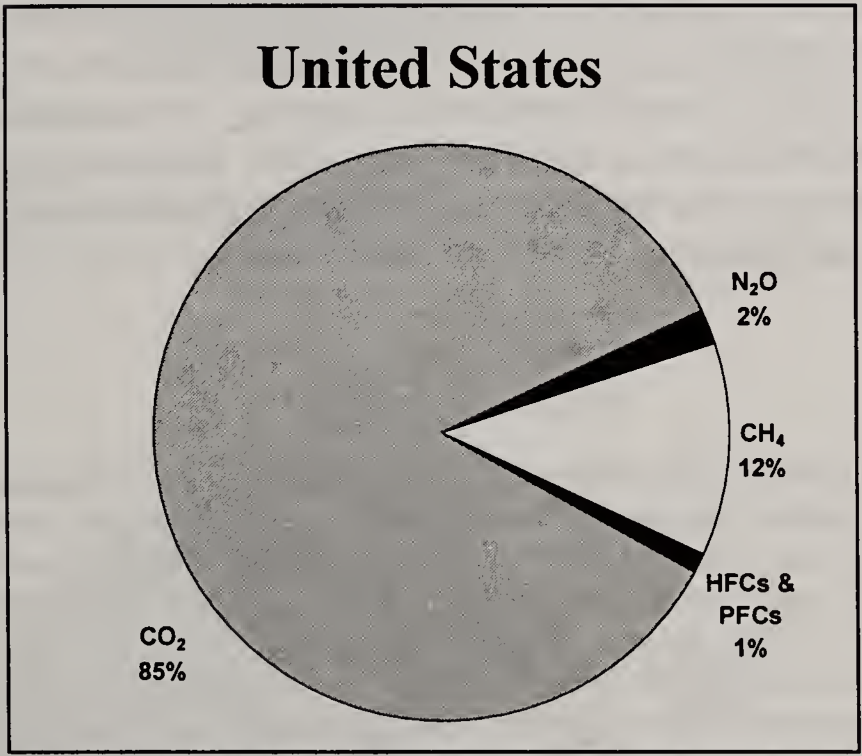
[11] Energy Information Administration (EIA), *Emissions of Greenhouse Gases in the United States 1987-1994*. October, 1995. U.S. Department of Energy. The EIA report provides inventory figures in million metric tons of carbon equivalent. These figures were converted to the units used in this inventory using the CO_2/C molecular weight ratio of 44/12 and a conversion factor of 1.1023 short tons per metric ton.

Figure II-1
Contribution to 1990 Inventory by Greenhouse Gas
(by percentage, in CO_2-equivalent)



Source: MA Inventory, Table II-1 (in-state emissions only)



Source: Energy Information Administration (EIA), *Emissions of Greenhouse Gases in the United States, 1987-1994. October 1995*, US Department of Energy.

Overall, the Massachusetts economy is less carbon-intensive than the U.S. economy. Without including upstream fuel-cycle emissions, the state's 1990 inventory amounted to 1.49 pounds of carbon dioxide equivalent per dollar of gross state product. This compares to a national ratio of 2.68 pounds of carbon dioxide equivalent emissions per dollar of gross domestic product for the nation as a whole.[12] Including the upstream

[12] Based on a 1990 Massachusetts gross state product of $129.7 billion (in 1987$) and a 1990 U.S. gross domestic product of $4,877.5 billion (in 1987$). Sources: MA Division of Energy Resources (DOER) and EIA, *1992 Energy Facts*, U.S. Department of Energy, Oct. 29, 1993. (DOE/EIA-0469(92)).

fuel-cycle emissions associated with energy use in Massachusetts increases the state ratio to 1.78 pounds of carbon dioxide equivalent emissions per dollar of gross state product.

While Massachusetts greenhouse gas emissions are relatively lower than emissions for the United States as a whole, they are high compared to the emissions levels of most other countries. In 1989, the global median per capita emissions rate was just 3.3 tons of carbon dioxide equivalent per person.[13] Thus, U.S. per capita emissions in 1990 were approximately eight times the global median and Massachusetts per capita emissions were approximately six times the global median (including upstream fuel cycle emissions). Even compared to similarly industrialized countries such as Japan and Germany, the state -- like the nation as a whole -- uses more energy and generates higher emissions per capita.[14] In fact, carbon dioxide emissions from fossil fuel combustion in Massachusetts alone would have ranked the state 31st among the nations with the highest emissions in 1990, ahead of such countries as Egypt, Greece, and Austria.[15] The United States as a whole remains by far the world's single largest emitter of carbon dioxide, accounting for more than 20% of global carbon dioxide emissions in recent years.[16]

Figure II-2 shows the relative contribution of major source categories in the Massachusetts inventory compared to the national inventory. The relatively smaller contribution of greenhouse gas emissions from industrial production processes and from the agricultural sector in Massachusetts results in energy use contributing a proportionately larger fraction of the overall inventory: emissions generated by fuel production and energy consumption account for 95.3% of the state inventory compared to 88.4% of the national inventory.[17]

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[13] World Resources Institute (in collaboration with the United Nations Environment Programme and the United Nations Development Programme), *World Resources 1992-93.* Oxford University Press, 1992, p. 209. Note that the World Resources figures, given in metric tons, were converted to short tons for purposes of this comparison. Note also that the World Resources data were for 1989. This was judged to be sufficiently close to 1990 for purposes of this comparison.

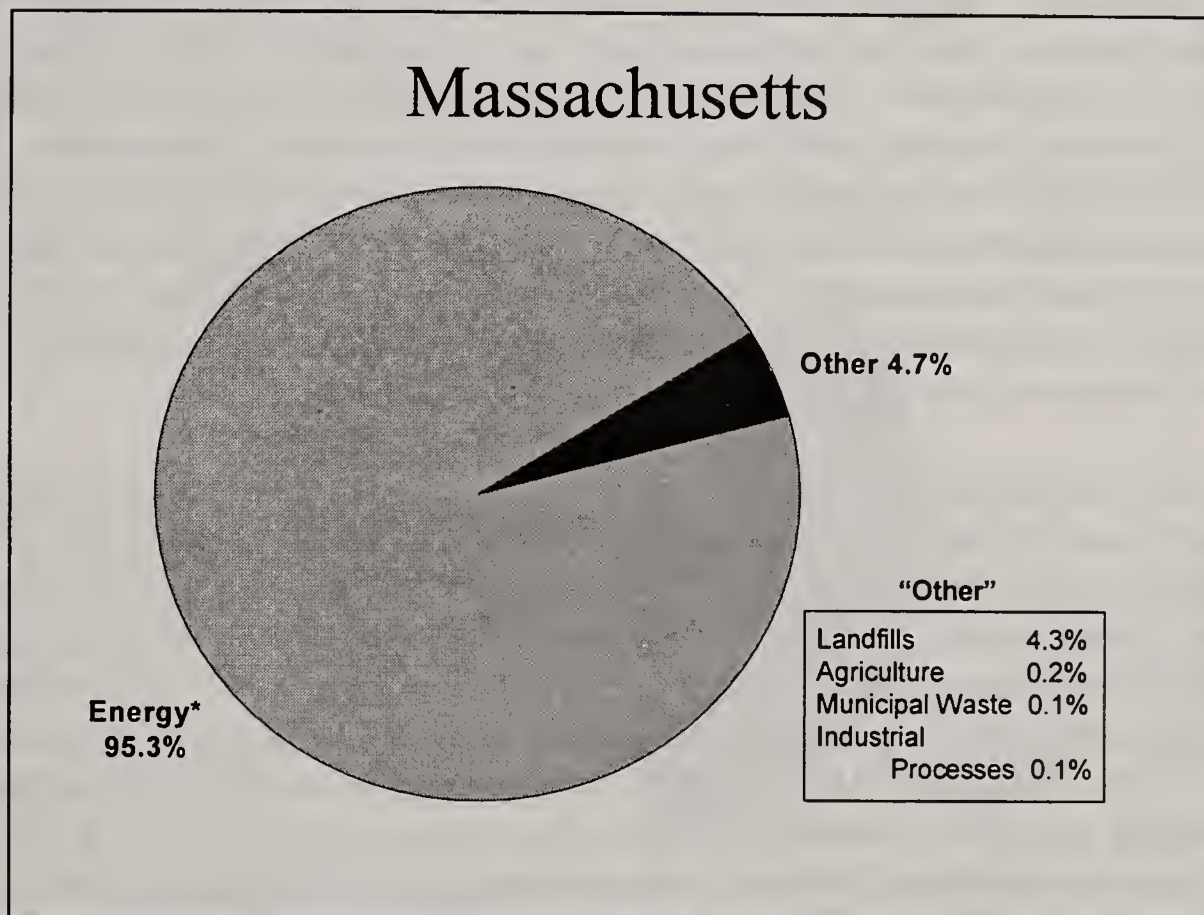
[14] Per capita, U.S. carbon dioxide emissions from fossil fuel burning were more than double those of Japan and 80% higher than those of Germany in 1994. *Source:* Lester Brown, et al, *State of the World 1996.* Worldwatch Institute, 1996. Table 2-2, p. 30.

[15] World Resources Institute, *op cit.*, p. 211, Table 13.6. See note to the data in footnote 12. Massachusetts direct fossil fuel carbon dioxide emissions (i.e. not including upstream fuel cycle) were used for this comparison: 89.1 million tons carbon dioxide.

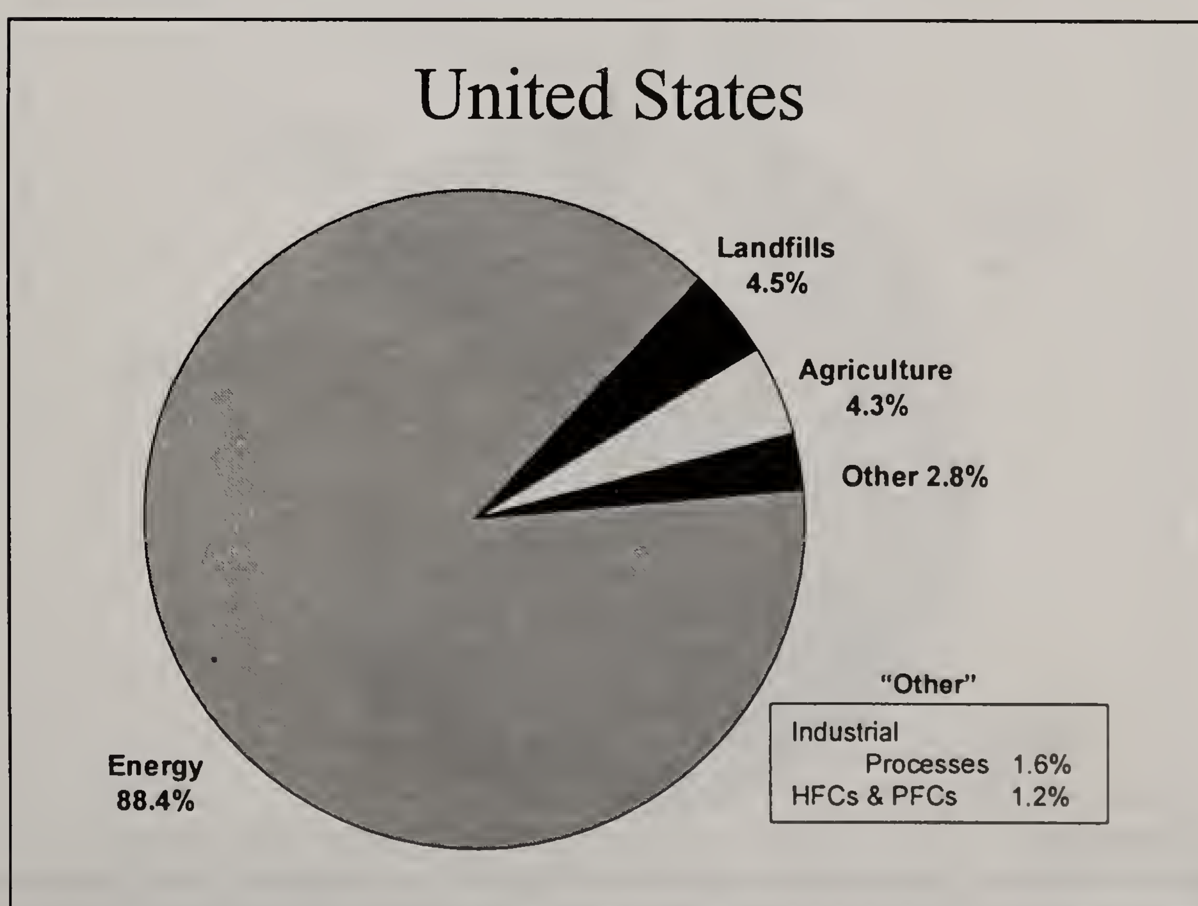
[16] Roger Doyle, "Carbon Dioxide Emissions," *Scientific American,* May 1996, p. 24. After the United States, the world's largest emitters of carbon dioxide from fossil fuel burning are currently China, Russia, Japan, Germany and India. China's share of world emissions has been growing rapidly in recent years and may overtake the U.S. contribution within the next few decades. See Lester Brown, et al, *State of the World 1996,* Worldwatch Institute, 1996, p. 30, Table 2-2.

[17] The Massachusetts figure includes emissions from electricity imports, as well as from the upstream fuel-cycle (counted here as part of the emissions attributable to fuel use). Note that these comparative figures may be slightly skewed by the fact that this Massachusetts inventory does not include halocarbons and related compounds, and by the fact that a figure for U.S. methane emissions associated with municipal wastewater was not included in the national inventory data. Source for all U.S. data: EIA, 1995, *op cit.*

Figure II-2
Sources of 1990 Greenhouse Gas Emissions
(by percentage, in CO_2 equivalent)



Source: MA Inventory, Table II-2.
* Includes imported electricity and upstream fuel-cycle emissions.



Source: EIA 1995 (via MA inventory, Table ES-3).

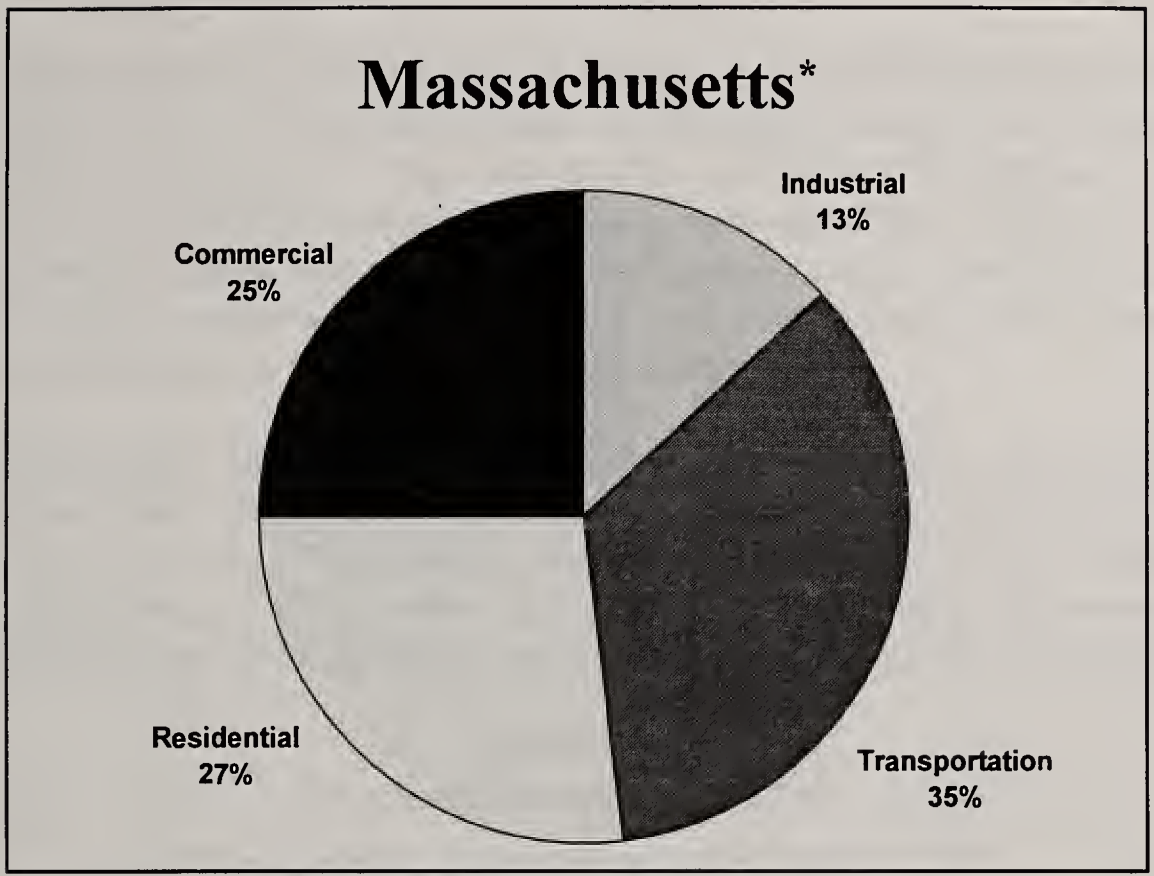
Considering just direct carbon dioxide emissions from fossil fuel consumption, Figure II-3 shows the breakdown by different end-use sectors for Massachusetts and the U.S. as a whole (upstream fuel cycle emissions and non-CO_2 emissions are not included in this comparison). The most striking difference between the state and national figures is the much smaller role of the industrial sector in Massachusetts. Whereas this sector contributes the largest share of carbon dioxide emissions from fossil fuel use in the national inventory, industry is the *least* important end-use sector in Massachusetts (note that electric utilities are not counted here as part of the industrial sector since their emissions are associated with electricity production for end-uses in other sectors). Instead, the transportation sector is the leading source of end-use carbon dioxide emissions in Massachusetts, and the residential and commercial sectors assume a relatively larger role than they do in the national inventory.

The role played by land-use changes, carbon sequestration in forests, and other land-use/biomass related sources is more difficult to compare. Approximately 33% of the United States' total land area is classified as forest. By comparison, forests are more prevalent in Massachusetts, accounting for almost 60% of the state's total land area. The U.S. Energy Information Administration (EIA) has estimated that the approximately 735 million acres of total U.S. forest land sequestered a net 497 million tons of carbon dioxide in 1990.[18] By comparison, Massachusetts' three million acres of forest are estimated in this inventory to have sequestered a net 8.9 million tons of carbon dioxide in 1990. Thus, while Massachusetts forests account for approximately 0.4% of the nation's forested acreage, they account for almost 1.8% of the national net forest sequestration estimated by EIA.[19]

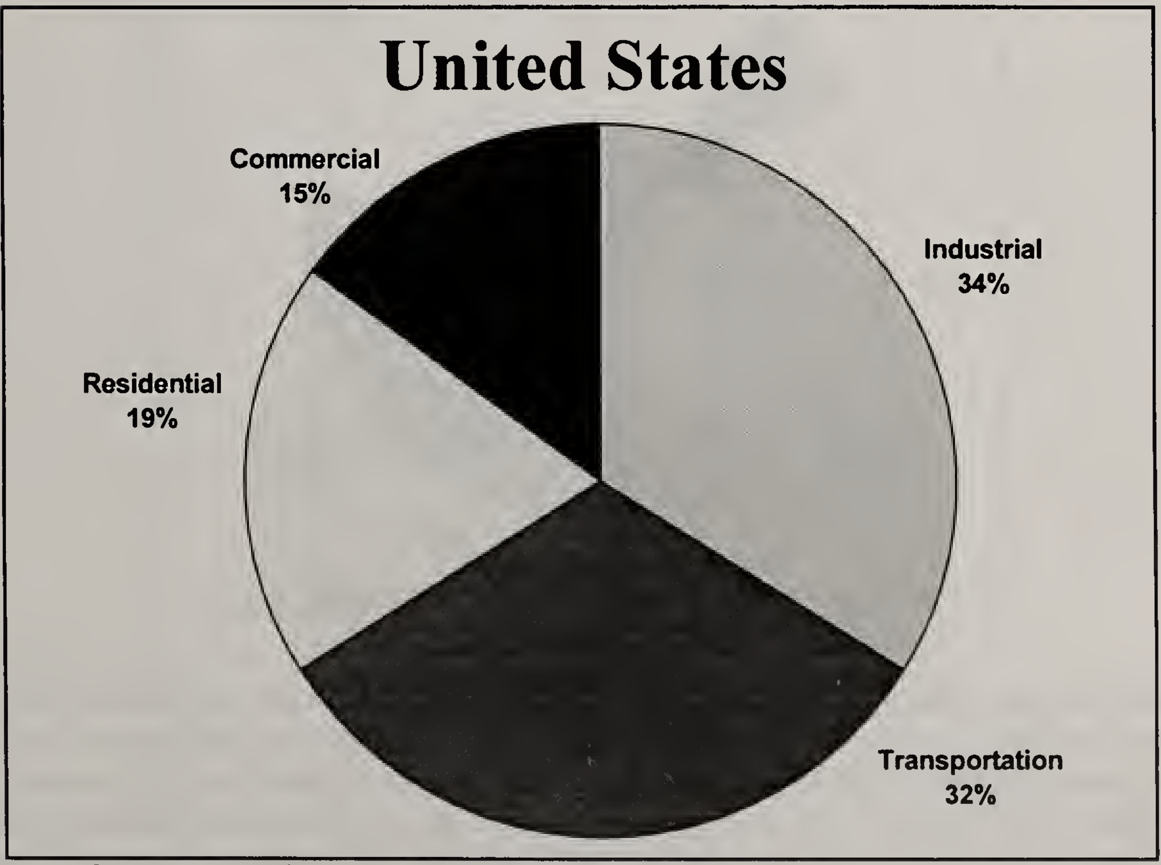
[18] EIA, 1995, *op cit.*

[19] Based on these figures, Massachusetts forests would appear to be sequestering more than four times as much carbon dioxide per acre than the average acre of forest nationally. It is not known whether this reflects differences in forest composition, in the classification of forest lands, or in the calculation methodology used to estimate state vs. national forest sequestration.

Figure II-3
1990 Carbon Dioxide Emissions from Energy Use
by End-Use Sector



Source: MA Inventory, Table II-2
* Includes imported electricity, but not upstream fuel-cycle emissions.



Source: EIA (via MA Inventory, Table ES-3)

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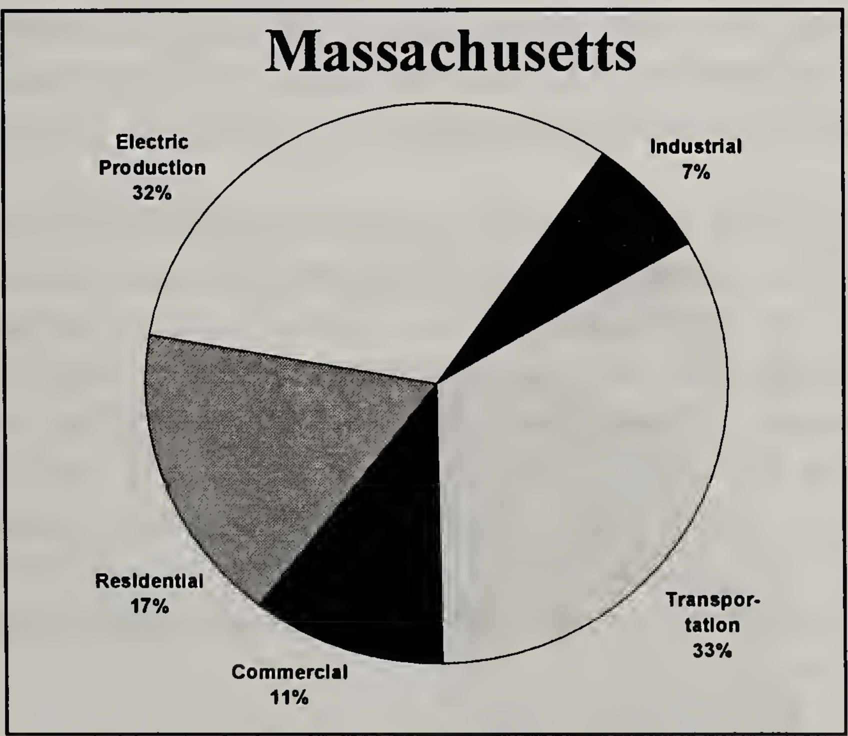
III. FOSSIL & BIOMASS FUEL COMBUSTION

A. Overview & Discussion

In Massachusetts, as in the nation as a whole, the combustion of carbon-based fuels -- including all fossil fuels and biomass -- is the predominant anthropogenic source of greenhouse gas emissions. Carbon dioxide and, to a lesser extent, methane, nitrous oxide and other pollutants are released as direct by-products of fuel combustion. Energy use and greenhouse gas emissions also occur during the extraction, processing, and transport of fuels - in other words, throughout the entire fuel cycle. These "upstream" emissions are addressed in Section IV of this inventory.

Massachusetts, like other states (and, indeed, all industrialized economies), relies heavily on fossil fuels. Fossil fuels used in the state include coal, petroleum products, and natural gas. In 1990, 32% of primary energy demand in the Commonwealth was for electricity production, 33% for transportation, and 35% for homes and businesses to provide space and water heating and to power industrial processes (see Figure III-1).[20]

Figure III-1
Primary Energy Use in 1990



Source: DOER SAFER Model

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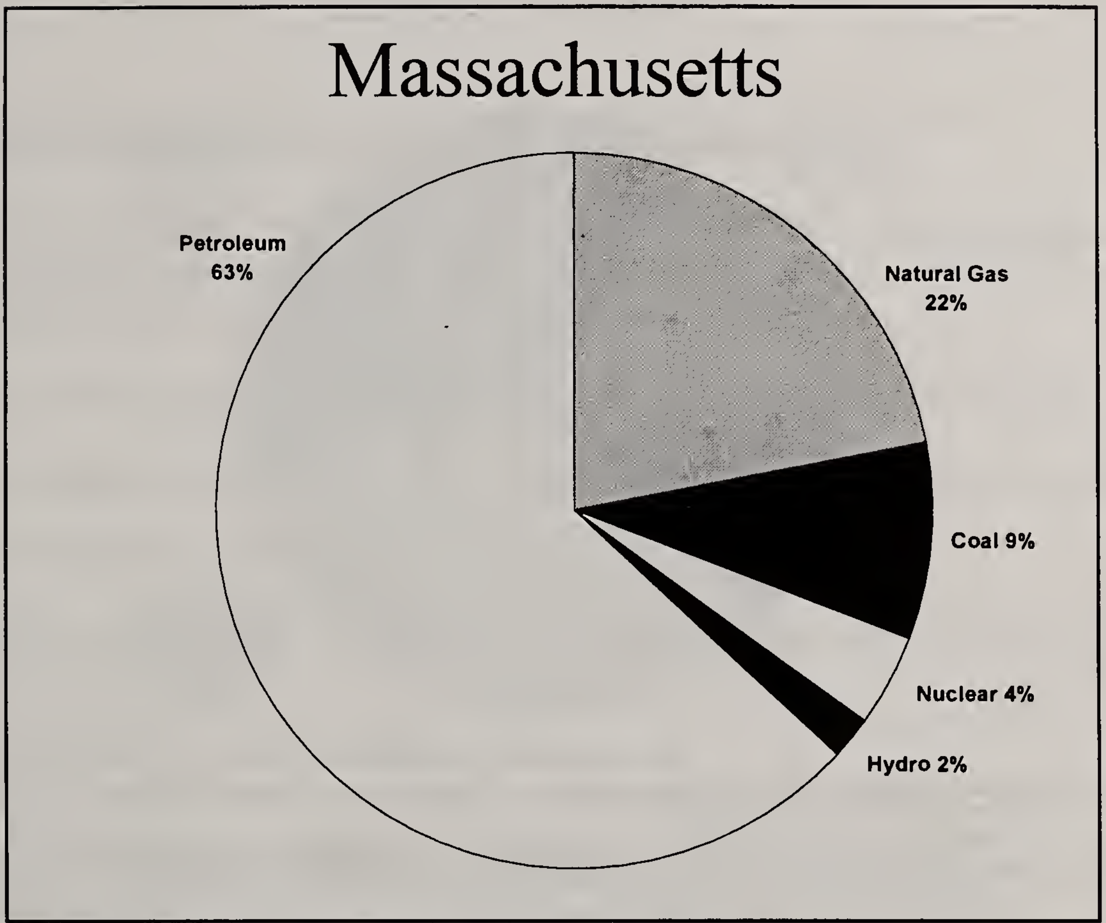
[20] A distinction is frequently made between "primary" and "end-use" energy consumption. Fuels, such as natural gas, oil, and coal, are considered primary forms of energy. Thus, primary energy use refers to the direct consumption of a fossil, nuclear, or biomass fuel. The energy content of these fuels may be used to serve an immediate end-use, such as moving a car, or it can be transformed into another energy form, such as electricity. Electricity is produced from primary fuels to serve other energy end-uses, such as lighting. Thus, the residential, commercial, and industrial sectors are all primary energy users to the extent that they directly burn fuels like natural gas and oil for space and water heating, and they are also end-users of energy in the form of electricity. Electricity production, by contrast, is a primary energy use sector, but not an end-use sector.

One salient feature of Massachusetts' energy economy is its unusually heavy dependence on petroleum products (e.g. gasoline, diesel, and heating oil) compared to the rest of the U.S. (see Figure III-2). Combustion of petroleum-based fuels is also the state's largest source of carbon dioxide emissions. Not surprisingly, much of the demand for petroleum in Massachusetts comes from the transportation sector. However, what is unique in Massachusetts is the extent to which petroleum is important in other energy use sectors and in electricity production. In fact, fully half of Massachusetts' petroleum consumption in 1990 was in the form of fuel oils for non-transportation uses. Of these, space heating and electricity production were among the most important. In 1990, oil provided almost half of Massachusetts' total energy requirements for residential space heating, compared to only 15% for the U.S. as a whole. Oil also accounted for 38% of electricity production in the state, compared to just 4% of electricity production nationwide. Figure III-3 shows the contribution to Massachusetts' energy-related carbon dioxide emissions from different fuel types (it does not include upstream fuel cycle emissions or net electricity imports).

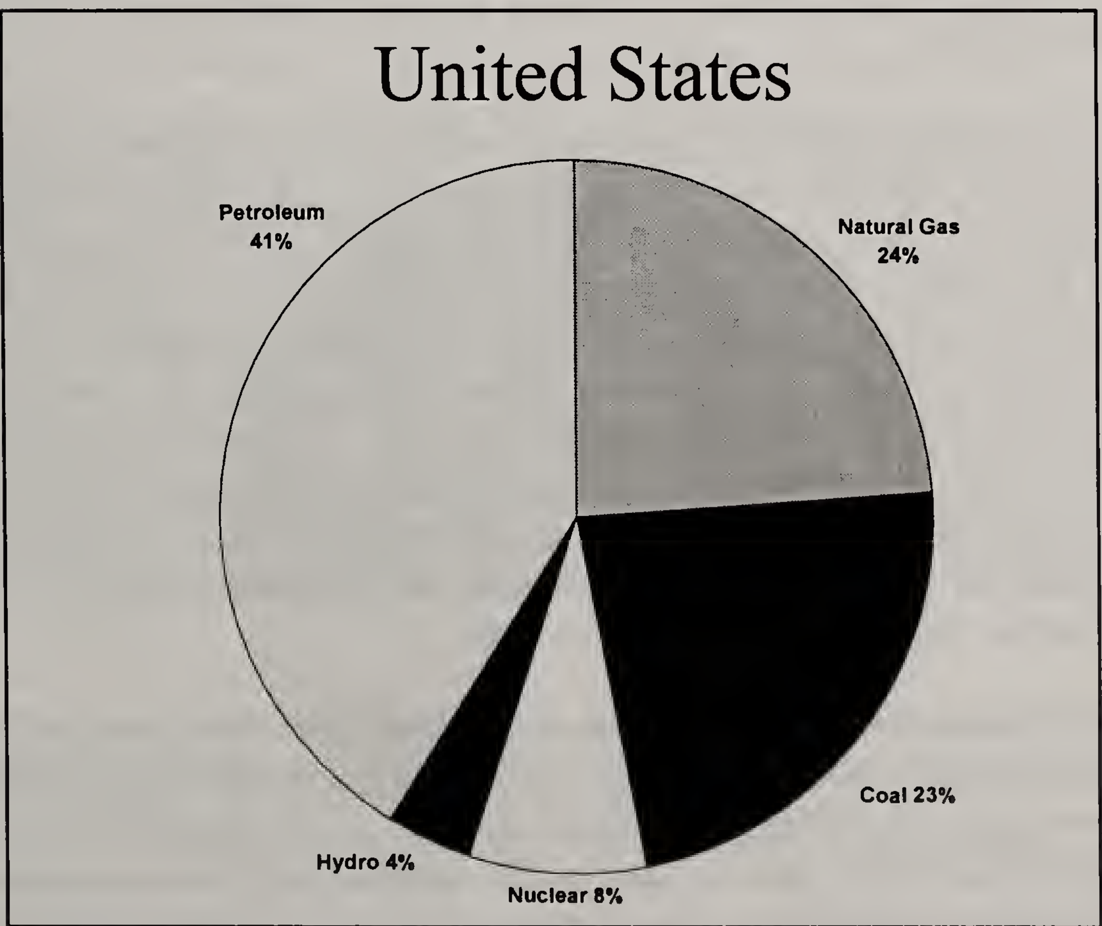
In Massachusetts, the transportation sector is responsible for the largest single share of greenhouse gas emissions from primary energy consumption, followed closely by electricity production. Emissions associated with electricity production, however, can be assigned to the residential, commercial, and industrial sectors that ultimately use the electricity. Apportioning total utility emissions to these "end-use" sectors, based on their contribution to overall electricity demand, leaves the transportation sector with the largest share of emissions, followed by the residential sector, the commercial sector, and, lastly, the industrial sector (see Figure II-3, above).

In addition, almost all combustion processes produce emissions of methane (CH_4) and nitrous oxide (N_2O) greenhouse gases. They also produce so-called "criteria pollutants" that are regulated under the Clean Air Act for local and regional air quality reasons, but which may also contribute indirectly to global climate change (see discussion in Part D of this Section). The criteria pollutants considered in this inventory (see Part D) are carbon monoxide (CO), volatile organic compounds (VOC), and nitrogen oxides (NOx). Emissions of these pollutants are much more difficult to estimate, but they are generally emitted in significantly smaller quantities than carbon dioxide. Because their effects are highly uncertain, they are considered separately from the chief greenhouse gases in this inventory.

Figure III-2
Energy Use by Source in 1990
(percentage of total Btu consumption)

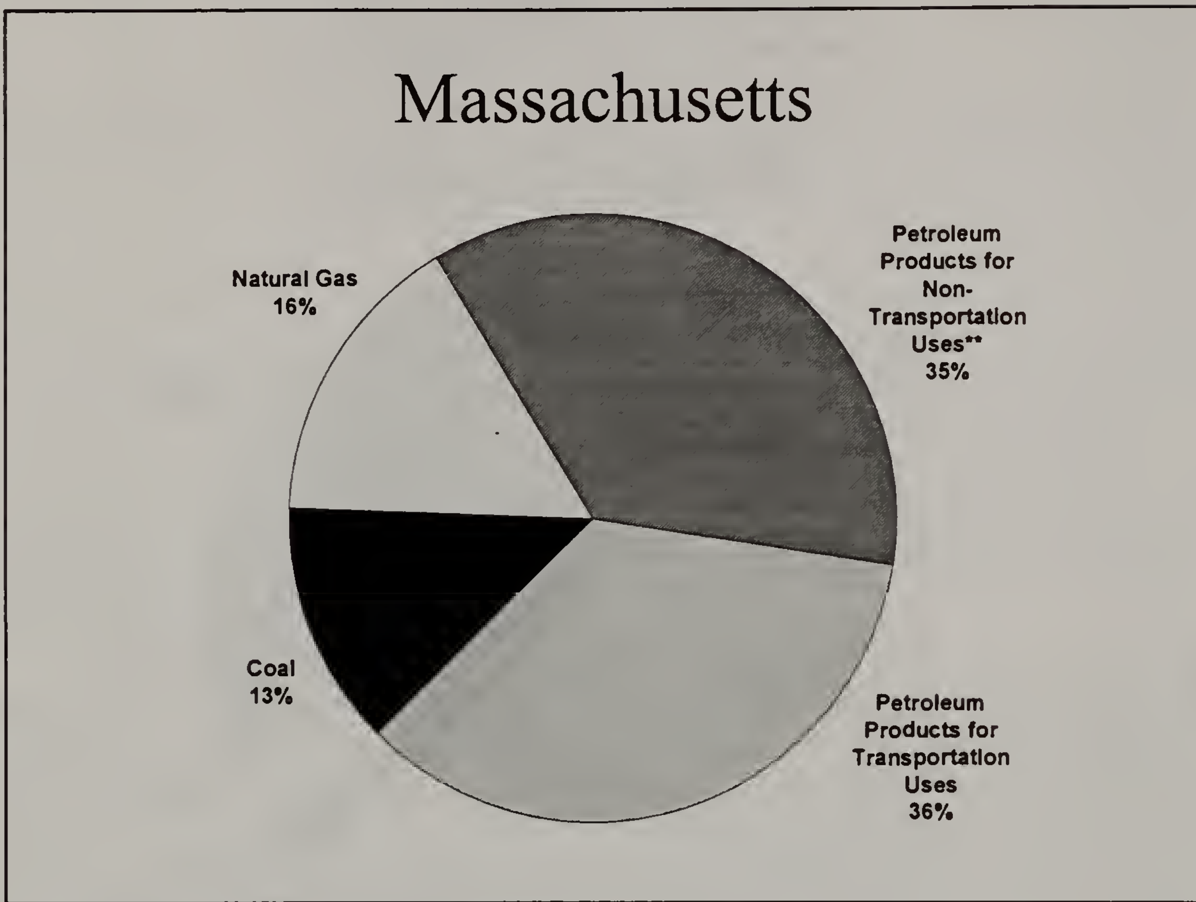


Source: DOER, *The Massachusetts Energy Plan*, 1993.



Source: Ibid.

Figure III-3
Carbon Dioxide Emissions by Fuel Type in 1990*



Source: DOER SAFER Model.
* Includes net electricity imports; but does not include upstream fuel-cycle emissions.
** Non-transportation uses of petroleum products include space and water heating, electricity production and industrial processes.

B. Methodology

The calculations needed to estimate greenhouse gas emissions from fossil fuel consumption begin with state data on fuel consumption. The basic methodology for calculating carbon dioxide emissions, as outlined in the *Workbook*, consists of multiplying the quantity of fuel consumed by the carbon content of the fuel, making an adjustment for incomplete oxidation, and finally converting this number to tons of carbon dioxide. The tables in this Section present carbon dioxide emissions from fossil and biomass fuel combustion by *primary* energy use sector. To generate the summary tables presented in Section II, aggregate electric utility emissions were subsequently distributed among the residential, industrial, and commercial end-use sectors. Methane, nitrogen oxide and other indirect greenhouse gas emissions are addressed separately from carbon dioxide emissions (see section D in this Section).

Fuel consumption figures provided in the subsequent tables are based on the SAFER (State Annual Forecast of Energy Resources) model, which was developed by the Massachusetts Division of Energy Resources (DOER) to forecast and analyze energy needs and resources for the state.[21] The SAFER outputs for 1990 are consistent with fuel

[21] Appendix A contains a description of DOER's SAFER model.

consumption recorded in the State Energy Data (SEDS) database maintained by the federal Energy Information Administration (EIA). Carbon content coefficients by fuel type and percent oxidation assumptions are taken from Part I of the *Workbook*. The following sample calculation is provided to demonstrate the approach used to calculate carbon dioxide emissions from fuel combustion. Complete data tables are found in Appendix B.

Sample Calculation for Emissions from Fossil Fuel Consumption:

Total 1990 Massachusetts consumption of motor vehicle gasoline in the transportation sector was 290,049,000 million Btu. Multiplying by the Carbon Content Coefficient for gasoline (from *Workbook* Table 1-3)[22] yields total potential carbon emissions:

290,049,000 mmBtu x 42.8 lbs C/mmBtu x 1 ton/2000 lbs = 6,207,049 tons C

Adjusting potential carbon emissions for incómplete combustion yields actual emissions:

6,207,049 tons C x 99% = 6,144,978 tons C

Multiplying the tons of carbon emissions by the molecular weight ratio of CO_2 to C yields carbon dioxide emissions:

6,144,978 tons C x 44/12 = **22,531,586 tons CO_2**

A special note is in order with respect to emissions from wood and municipal solid waste combustion, which are included in some of the following tables. Wood is the only biomass fuel used in significant quantities in Massachusetts and, provided it is harvested on a sustainable basis, does not create a net contribution to global warming because carbon emissions from combustion are offset by a corresponding sequestration of carbon in biomass regrowth. Municipal solid waste combustion presents a more difficult problem because the waste contains both biomass components (e.g., wood and paper) as well as petroleum-based components (e.g., plastics and oils). Rather than attempt to estimate what portion of the waste can be considered a biomass vs. fossil-based fuel, emissions from municipal solid waste combustion are treated like biomass emissions (i.e., assumed to have no net contribution) and are not included in aggregate emissions totals.[23] Emissions from wood combustion are accounted for, together with carbon uptake from biomass regeneration, in Section IX, Forest Management and Land-Use Changes. However, emissions from wood and waste combustion are also included in the summary tables for this section in the interest of providing a complete picture of energy-related emissions for each sector.

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[22] As noted previously, all references to the *Workbook* refer to EPA's *State Workbook, Methodologies for Estimating Greenhouse Gas Emissions* (Second Edition, January 1995). In most cases, calculation methodologies, coefficients, and default values are taken from the *Workbook*.

[23] Since solid waste undoubtedly contains some non-renewable fraction, emissions from electricity production are somewhat understated as a result. The *Workbook*, however, provides no clear guidance on this point, and municipal solid waste combustion generally does not appear to be included in other national and international inventories.

C. Emissions of Carbon Dioxide from Primary Energy Use by Sector

1. Residential Fuel Consumption

Carbon dioxide emissions from residential sector consumption of fossil fuels are summarized in Table III-1. Distillate fuel oil and natural gas are the main contributors, as these are common fuels for space heating and water heating in the Commonwealth. Note that household electricity use is not included in this summary of primary energy consumption (see Section III.C.5). Obviously, this is another important source of overall greenhouse gas emissions attributable to the residential sector. Assigning 34% of total emissions associated with electricity consumption to the residential sector, based on the residential share of overall electricity demand, adds another 9.7 million tons of carbon dioxide emissions to the end-use global warming contribution of this sector, bringing the total energy-related residential contribution to 24.0 million tons.

Table III-1
1990 Emissions from Residential Fuel Consumption

Fuel Type	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Carbon Oxidation	Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Heating Oil	100,696,000	44.0	2,215,312	99%	2,193,159	8,042
Natural Gas	99,700,000	31.9	1,590,215	99.5%	1,582,264	5,802
Kerosene	900,000	43.5	19,575	99%	19,379	71
LPG	4,899,000	37.8	92,591	99%	91,665	336
Coal, Anthracite	400,000	62.1	12,420	99%	12,296	45
Coal, Bituminous	300,000	56.0	8,400	99%	8,316	30
FOSSIL SUBTOTAL	**206,895,000**		**3,938,513**		**3,907,079**	**14,326**
Wood*	220,000	47.5%	104,500	90%	94,050	345
TOTAL	**207,115,000**		**4,043,013**		**4,001,129**	**14,671**

* Note: Wood consumption figures are given in tons (not mmBtu), and carbon content is expressed as a percentage by weight. CO_2 emissions from wood combustion are not included in state totals, as explained in Section III.B.

2. Commercial Fuel Consumption

Carbon dioxide emissions from commercial sector consumption of fossil fuels are summarized in Table III-2. The pattern is similar to that for the residential sector, with fuel oil and natural gas consumption for space and water heating accounting for the bulk of emissions associated with primary energy use in this sector. Again, although not reflected in this summary of primary energy consumption, commercial electricity use is an important source of overall greenhouse gas emissions attributable to the commercial

sector (see Section III.C.5). Assigning 41% of total emissions associated with electricity consumption to the commercial sector, based on the commercial share of overall electricity demand, adds another 11.7 million tons of carbon dioxide emissions to the end-use global warming contribution of this sector, bringing its total to 21.6 million tons.

Table III-2
1990 Emissions from Commercial Fuel Consumption

Fuel Type*	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Carbon Oxidation	Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Heating Oil	41,028,000	44.0	902,616	99%	893,590	3,276
Residual Oil	32,212,000	47.4	763,424	99%	755,790	2,771
Natural Gas	61,900,000	31.9	987,305	99.5%	982,368	3,602
Kerosene	791,000	43.5	17,204	99%	17,032	62
LPG	1,017,000	37.8	19,221	99%	19,029	70
Gasoline	452,000	42.8	9,673	99%	9,576	35
Coal, Anthracite	300,000	62.1	9,315	99%	9,222	34
Coal, Bituminous	500,000	56.0	14,000	99%	13,860	51
TOTAL	**138,200,000**		**2,722,759**		**2,700,468**	**9,902**

* Note that emissions for wood consumption are not shown here; commercial uses of wood are included in the industrial use category in the next section because separate figures for the commercial sector were not available.

3. Industrial Fuel Consumption

Table III-3 presents primary energy consumption and carbon dioxide emissions for the industrial sector. Calculations for this sector are complicated by the fact that not all fossil fuels used by the industrial sector are combusted. Prominent examples include lubricants; asphalt and road oil used in highway construction; and natural gas and petrochemical feedstocks used in industrial processes. Depending on the non-fuel uses involved, carbon may either be oxidized (thereby contributing carbon dioxide emissions) or stored (in which case there are no emissions).

Calculating carbon dioxide emissions for the industrial sector therefore involved some additional steps. First, total consumption of various fuel types was multiplied by the fraction typically used for non-fuel purposes based on national averages reported in the EIA's Annual Energy Review.[24] This subset was then multiplied by a factor representing the fraction of carbon that can be assumed to be stored in non-fuel uses (from *Workbook*, Table D1-3). The remaining carbon content associated with non-fuel

[24] EIA, *1990 Annual Energy Review*. p. 33, Table 1-15. U.S. Department of Energy, 1992.

use was assumed to be oxidized, together with all the carbon associated with fuel use. A sample calculation is provided below.

Sample Calculation for Emissions from Industrial Sector Fuel Consumption:

Total 1990 Massachusetts industrial consumption of LPG was 2,966,000 million Btu. Based on national figures provided by EIA, non-fuel uses account for 96.4% of industrial LPG consumption. Thus,

fuel uses = (1-0.964) x 2,966,000 mmBtu = 106,776 mmBtu
non-fuel uses = 0.964 x 2,966,000 mmBtu = 2,859,224 mmBtu

The total carbon content of all the LPG consumed for both fuel and non-fuel uses, using the coefficient provided in *Workbook* Table 1-3 =

2,966,000 mmBtu x 37.8 lbs C/mmBtu x 1 ton/2000 lbs = 56,057 tons C

However, according to *Workbook* Table 1-4, 80% of non-fuel use of LPG is stored, producing no carbon dioxide emissions. Stored carbon associated with non-fuel uses of LPG =
2,859,224 mmBtu x 0.8 x 37.8 lbs C/mmBtu x 1 ton/2000 lbs = 43,231 tons C

Subtracting this amount from the total carbon content of all the LPG consumed:

56,057 tons C - 43,231 tons C = 12,826 tons C

Adjusting for incomplete combustion yields:

12,826 tons C x 0.99 = 12,698 tons C

Converting carbon emissions to carbon dioxide emissions yields:
12,698 tons C x 44/12 = **46,558 tons CO_2**

A summary of results for different industrial fuel uses is provided in Table III-3. Complete tables showing all the factors for fuel vs. non-fuel use and carbon storage are provided in Appendix B, Table 3a. In addition to primary energy use shown in Table III-3, the industrial sector accounts for 22% of the state's electricity consumption (see Section III.C.5), which would add another 6.3 million tons of carbon dioxide emissions to the end-use global warming contribution of this sector, bringing its total to 11.2 million tons.

Table III-3
1990 Emissions from Industrial Fuel Consumption

Fuel Type	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Stored Carbon* (tons)	Net** Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Asphalt & Road Oil	7,542,000	45.5	171,581	159,741	11,721	43
Heating Oil	10,763,000	44.0	236,786	10,419	224,104	822
Residual Oil	14,068,000	47.4	333,412	14,670	315,554	1,157
Natural Gas	28,600,000	31.9	456,170	29,651	424,386	1,556
Kerosene	85,000	43.5	1,849	81	1,750	6
LPG	2,966,000	37.8	56,057	43,231	12,698	47
Lubricants	1,949,000	44.6	43,463	21,731	21,514	79
Misc. Petrol.	10,763,000	44.7	240,553	10,584	227,669	835
Gasoline	1,864,000	42.8	39,890	0	39,491	145
Coal, Anthracite	100,000	62.1	3,105	19	3,056	11
Coal, Bituminous	1,700,000	56.0	47,600	286	46,841	172
FOSSIL SUBTOTAL	**80,400,000**		**1,630,465**	**290,414**	**1,328,783**	**4,872**
Wood***	64,000	47.5%	30,400	90%	27,360	100
TOTAL	**80,464,000**				**1,356,143**	**4,972**

* Based on share of non-fuel use and percent carbon stored of non-fuel use. See Appendix B, Table 3a.
** Equals total carbon minus stored carbon.
*** Note: Wood consumption figures are given in tons (not mmBtu), and carbon content is expressed as a percentage by weight. Wood figures here include commercial sector consumption. CO_2 emissions from wood combustion are not included in state totals, as explained in Section III.B.

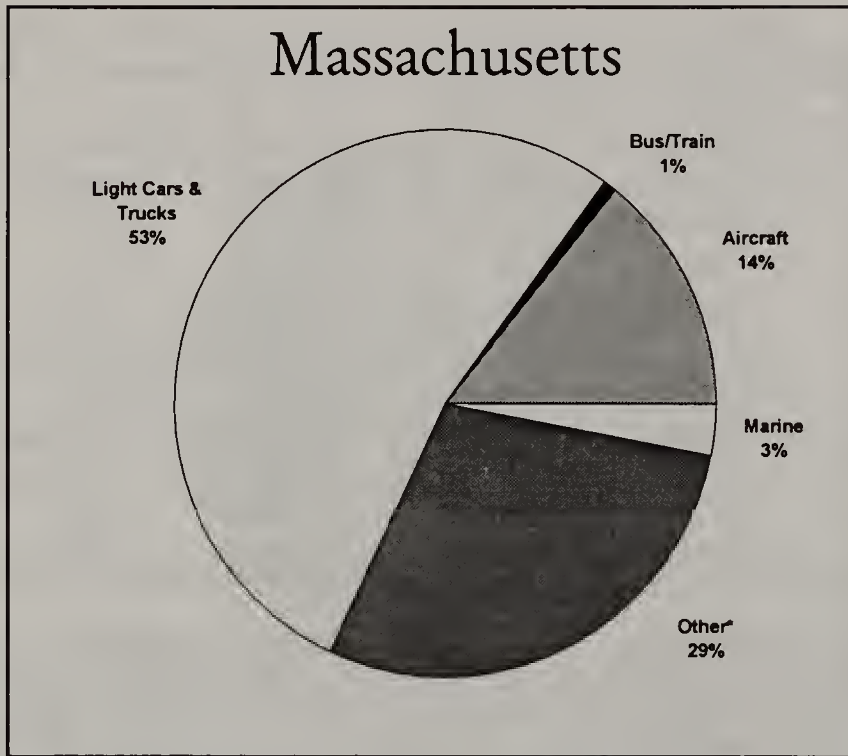
4. Transportation Fuel Consumption

Transportation accounts for the single largest sector of primary energy consumption in Massachusetts and makes the largest contribution to the state's 1990 greenhouse gas inventory. It is also the fastest growing sector of energy demand in the state. Almost all of these emissions come from consumption of petroleum fuels. Figure III-4 shows a breakdown of energy consumption by different modes of transportation. Carbon dioxide emissions by fuel type are summarized in Table III-4.

Table III-4
1990 Emissions from Transportation Fuel Consumption

Fuel Type	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Carbon Oxidation	Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Aviation Fuel	500,000	41.6	10,400	99%	10,296	38
Diesel Fuel	43,692,000	44.0	961,224	99%	951,612	3,489
Jet Fuel	55,490,000	43.5	1,206,908	99%	1,194,838	4,381
LPG	200,000	37.8	3,780	99%	3,742	14
Lubricants	2,899,000	44.6	64,648	99%	64,001	235
Gasoline	290,049,000	42.8	6,207,049	99%	6,144,978	22,532
Residual Oil	8,698,000	47.4	206,143	99%	204,081	748
TOTAL	**401,528,000**		**8,660,150**		**8,573,549**	**31,436**

Figure III-4
Energy Consumption by Transportation Mode in 1992



Source: DOER, *The Massachusetts Energy Plan,* 1993.
* "Other" includes vehicles classified as "heavy duty" and "off-road."

5. Electric Utility Fuel Consumption

The production of electricity to meet power demands in the residential, commercial, and industrial sectors[25] accounts for a large share of overall primary energy consumption and ranks a close second to the transportation sector as a source of greenhouse gas emissions. Together, in-state electricity production and electricity imports generated almost 28.6 million tons of carbon dioxide emissions (a close second to emissions from the transportation sector). In this section, in-state electricity production is considered separately from electricity imports, in order to avoid double counting emissions that may also be included in other states' inventories. Carbon dioxide emissions from in-state electricity production are summarized in Table III-5a, while emissions from net electricity imports are summarized in Table III-5b.

With regard to electricity production within the state, Massachusetts differs from the rest of the country in the greater extent to which oil is used to generate power. Correspondingly, coal -- which is the dominant electricity fuel in the rest of the nation -- is less important, accounting for just 28% of electricity production in Massachusetts, compared to 55% for the U.S. as a whole. Since coal is a more carbon intensive fuel than oil, this tends to reduce in-state greenhouse gas emissions from the electric utility sector relative to the U.S. The Commonwealth's relatively greater use of natural gas for

[25] A small amount of electricity is used in the transportation sector to power certain trains and buses. Most of this electricity is generated by state transportation authorities and is captured as primary energy consumption in Table III-4. In the future, the advent of electric vehicles and other electric modes of transportation should lead to increased electricity use by this sector.

electricity generation -- 15% in 1990 compared to 10% for the nation as a whole -- also helps to reduce its greenhouse gas emissions in the utility sector. On the other hand, carbon-free nuclear and hydropower, which together accounted for 31% of all electricity production in the U.S. in 1990, accounted for only 19% of Massachusetts electricity production. The net effect of these state vs. national differences is that in-state electricity production was, on the whole, slightly more carbon intensive than the national average, generating a total of 27 million tons of carbon dioxide in 1990, or about 1.5 pounds per kilowatt-hour (kWh). This compares to a national average figure of approximately 1.3 pounds per kWh.

Table III-5a
1990 Emissions from In-State Electricity Production

Fuel Type	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Carbon Oxidation	Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Heating Oil	2,800,000	44.0	61,600	99%	60,984	224
Residual Oil	147,800,000	47.4	3,502,860	99%	3,467,831	12,715
Natural Gas	58,100,000	31.9	926,695	99.5%	922,062	3,381
Coal, Bituminous	109,700,000	56.0	3,071,600	99%	3,040,884	11,150
FOSSIL SUBTOTAL	**318,400,000**		**7,562,755**		**7,491,761**	**27,470**
MSW*	19,060,000	54.5	519,390	99%	514,190	1,885
Nuclear	54,100,000	0	0		0	0
Wood**	4,370	47.5%	2,076	90%	1,870	7
TOTAL	**391,564,370**		**8,084,221**		**8,007,821**	**29,362**

* Municipal Solid Waste combustion is included for the sake of completeness. However, its emissions are not counted as a net contribution to the inventory. See discussion in Section III.B.

** Wood consumption figures are given in tons (not mmBtu), and carbon content is expressed as a percentage by weight. CO_2 emissions from wood combustion are not included in state totals, as explained in Section III.B.

Table III-5b
1990 Emissions from Net Electricity Imports
(numbers in parentheses indicate net exports from Massachusetts)*

Fuel Type	Energy Consumption (mmBtu)	Carbon Content (lbs C/mmBtu)	Total Carbon (tons)	Carbon Oxidation	Carbon Emissions (tons)	CO_2 Emissions (000 tons)
Residual Oil	6,321,000	47.4	149,808	99%	148,310	544
Natural Gas	1,955,000	31.9	31,182	99.5%	31,026	114
Coal	(23,037,000)	56.0	(645,036)	99%	(638,586)	(2,341)
System Purchases**					754,965	2,768
Nuclear	51,400,000	0	0	n/a	0	0
TOTAL					**295,715**	**1,084**

* Emissions associated with net exports are treated as negative values; that is, they are subtracted from the total.

** System purchases denote purchases of bulk electricity from the New England Power Pool (NEPOOL). Such purchases amounted to 5,649,400 megawatt-hours (MWH) in 1990. Since the precise fuel mix used to generate system purchases is unknown, a NEPOOL system average emissions rate of 0.49 tons CO_2 per MWH was used to estimate the associated carbon dioxide emissions.

However, Massachusetts is also a net importer of electricity, a significant portion of which is produced by nuclear power plants outside the state. In fact, approximately 20% of the state's total electricity demand is supplied by generating facilities outside the state. Emissions associated with these electricity imports are included in this inventory because they are generated to meet the immediate energy demands of Massachusetts citizens and businesses. They are summarized below. When electricity imports are considered together with in-state electricity production, the overall carbon intensity of power *consumed* in Massachusetts -- approximately 1.2 pounds per kWh -- is lower than the U.S. national average.

D. Other Greenhouse Gas Emissions

Carbon dioxide is the dominant, but not the only greenhouse gas produced in the combustion of fossil fuels. Other important greenhouse gases include methane (CH_4), and nitrous oxide (N_2O). In addition, other pollutants generated by fossil fuel combustion do not have direct warming effects in the atmosphere, but do contribute to chemical reactions that alter or create greenhouse gases, such as tropospheric ozone. The pollutants with an indirect greenhouse effect include carbon monoxide (CO), nitrogen oxides (NOx) and volatile organic compounds (VOC). The climate impacts of these pollutants are generally small relative to carbon dioxide. Moreover, calculating their inventories is more complicated, since, unlike carbon dioxide, these types of emissions are not a direct function of fuel properties.

Non-carbon dioxide emissions from fossil fuel combustion could be calculated using the emissions factors listed in Discussion Sections 13 and 14 of the *Workbook.* However, because Massachusetts already collects information on NOx, CO, and VOC, figures for statewide emissions of these pollutants were simply taken from existing inventories. The figures are broken down by mobile and stationary source categories. Massachusetts does not separately collect information on methane and nitrous oxide emissions, although some methane emissions are included in the VOC inventories. Since the methane share of overall VOCs in the state inventory is unknown, however, and since no information at all was available on N_2O, emissions of both of these greenhouse gases were estimated separately from "the bottom up" using the emissions factors provided in the *Workbook.* It must be cautioned that these estimates are probably quite imprecise, since the factors in the *Workbook* contain significant uncertainties. Summary results for methane and nitrous oxide are tabulated in Table III-6, while complete tables and a more detailed explanation of the methodology are provided in Appendix C.

Table III-6
Estimated 1990 CH_4 and N_2O Emissions from In-State Fuel Combustion*

Source Type	CH_4 Emissions (tons)	N_2O Emissions (tons)	Combined CO_2-equivalent** (000 tons)
Mobile	4,600	4,294	1,487
Stationary	1,814	2,683	903
TOTAL	**6,414**	**6,977**	**2,390**

* Includes emissions from in-state fuel combustion only, since the precise fuel mix used to generate imported electricity was not known.
** To generate CO_2-equivalent emissions, CH_4 emissions were multiplied by a global warming potential (GWP) of 24.5 and N_2O emissions were multiplied by a GWP of 320.

Table III-7 summarizes the 1990 inventory figures for carbon monoxide, nitrogen oxides, and volatile organic compounds emissions. As previously noted, the figures for VOC capture at least some of the methane inventory calculated above. Table III-7 does not provide carbon dioxide equivalents. That is because these types of pollutants contribute to global warming only indirectly, for example through the formation of tropospheric ozone (which functions as a greenhouse gas) or, in the case of carbon monoxide, by indirectly increasing methane concentrations in the atmosphere. Because their indirect influence on the greenhouse effect is highly variable and difficult to quantify, GWPs are not available for these types of pollutants, and they are not included in the summary tables and in the results sections of this inventory.

Table III-7
1990 State Inventory for CO, NOx, VOC Emissions*

Source Type	CO Emissions (tons)	NOx Emissions (tons)	VOC Emissions (tons)
Mobile	1,295,568	205,537	185,884
Stationary	149,548	139,528	148,023
TOTAL	**1,445,116**	**345,065**	**333,907**

* For some pollutant sources, emissions inventories were only available for the 5-month summer ozone season. In these cases ozone season emissions were multiplied by 12/5ths to obtain an annual estimate.
Source: Massachusetts Department of Environmental Protection, Division of Air Quality Control, "Overview: Massachusetts 1990 Base Year Emission Inventories," Oct. 25, 1994.

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IV. UPSTREAM EMISSIONS FROM FOSSIL FUEL PRODUCTION SYSTEMS

A. Overview & Discussion

The *Workbook* provides for the calculation of greenhouse gas emissions associated with natural gas and oil production systems, as well as coal mining. Since Massachusetts does not have any conventional, indigenous energy resources (besides biomass and municipal solid waste), these types of emissions sources do not exist within the state. However, as noted previously, there are certainly "upstream" greenhouse gas emissions associated with extracting, processing, transporting and distributing the fuels that are consumed within the state. although these emissions occur outside Massachusetts (and should be accounted for in the inventories of fuel producing states), they are nevertheless directly linked to energy use in the Commonwealth. Therefore, they are considered here in the interests of a more complete accounting of the state's responsibility for overall greenhouse gas loadings in the atmosphere. In order to avoid double-counting with other states' inventories, upstream emissions are presented separately in all summary tables.

B. Methodology

To obtain a rough estimate of greenhouse gas emissions associated with the extraction, processing, transport, and distribution of fossil fuels used in Massachusetts, an average emissions factor was applied to the state's total consumption of each different fuel type. The emissions factors used are taken from Mark DeLuchi's 1991 study, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* (Argonne National Laboratory). The DeLuchi study attempts to quantify greenhouse gas emissions at every stage of the full fuel cycle. It provides emissions factors in grams of carbon dioxide equivalent emissions per million Btu of delivered fuel. These factors include natural gas emissions from mines and oil wells, as well as natural gas leaks and flares; feedstock recovery and transport; fuel production and distribution; and fuel compression and liquefaction, where appropriate.

To calculate upstream full fuel-cycle emissions, the consumption of each major fuel type, expressed in million Btu, is totaled from the tables provided in Section III and multiplied by the DeLuchi emissions factors (a breakdown of the components of these factors from the DeLuchi study is provided in Appendix D). A few caveats are in order. First, the emissions factors used represent a national average and may not be entirely accurate for Massachusetts. For instance, to the extent that Massachusetts is more distant from its fuel sources than other states, it may require more upstream energy consumption

for transport and distribution.[26] Nevertheless, for purposes of providing an order of magnitude estimate of full fuel-cycle emissions, the DeLuchi factors represent probably the most complete available estimates.

C. Upstream Emissions Associated with Massachusetts Fuel Use

Table IV-1 presents upstream greenhouse gas emissions associated with the consumption of nuclear and fossil fuels in Massachusetts, based on the methodology outlined above. These figures do not include upstream emissions associated with electricity imports since the precise fuel mix used to produce electricity that was imported to Massachusetts from out of state was not known. Overall, these upstream emissions are clearly significant, adding more than 20% to the total carbon dioxide emitted when fuels are eventually consumed.

Table IV-1
1990 "Upstream" Emissions from Massachusetts In-State Fuel Use

Fuel Type	Consumption (mmBtu)	Emissions Factor (lbs CO_2-Equiv/mmBtu)*	CO_2-Equivalent Emissions (000 tons)
Gasoline**	292,865,000	46.82	6,856
Diesel***	43,692,000	35.19	769
Fuel Oil	358,065,000	34.11	6,107
Coal	113,000,000	19.97	1,128
Natural Gas	248,300,000	24.50	3,042
Nuclear	51,400,000	32.11	825
TOTAL	**1,107,322,000**		**18,727**

* Emissions factors represent DeLuchi's estimates, which are given in CO_2-equivalent grams per mmBtu, converted to pounds per mmBtu. They include non-CO_2 greenhouse gas emissions, such as methane, converted to CO_2-equivalents using global warming potentials (GWPs). See Appendix D.
** Includes aviation gasoline.
*** Fuel consumption figures given in Section II distinguish between distillate (heating) and residual oil, not between diesel and fuel oil. Hence, this calculation assumes that all the distillate oil consumed in the transportation sector (see Table III-4) is diesel; all other residual and distillate oil consumption in other sectors is categorized here as fuel oil.

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[26] Note that the DeLuchi factors are considerably higher than those used by the State of Wisconsin in its 1990 inventory of greenhouse gas emissions. See: Wisconsin Department of Natural Resources and Public Service Commission of Wisconsin, *Wisconsin Greenhouse Gas Emissions: Estimates for 1990*, December, 1993.

V. INDUSTRIAL PRODUCTION PROCESSES

A. Overview & Discussion

A small fraction of the overall Massachusetts greenhouse gas inventory is emitted as a direct by-product of industrial production processes. These emissions are in addition to the industrial sector's much larger contribution to emissions from the direct combustion of fossil fuels. The only industrial processes in Massachusetts for which data are available and for which the EPA has developed calculation methods are lime manufacture and limestone use.

Other industrial processes that may emit greenhouse gases apparently do not exist in the state on a scale that is captured by available information resources. According to the relevant Annual Reports from the U.S. Bureau of Mines, cement and soda ash (whose production would emit carbon dioxide) are not manufactured in reportable quantities in Massachusetts, nor is aluminum (whose production would emit two ozone-depleting perflourocarbons, CF_4 and C_2F_6). According to the office responsible for implementation of the state's Toxic Use Reduction Act (TURA), no figures for nitric acid and adipic acid production (which would emit N_2O) have been reported in Massachusetts (the TURA reporting threshold is 25,000 pounds).

There also does not appear to be any significant industrial process carbon dioxide production in Massachusetts (controlled quantities of carbon dioxide produced for purposes like recovering oil or providing carbonation for beverages). According to the state's leading carbonated beverage producer, its only in-state source of carbon dioxide for carbonation is a cogeneration plant, whose emissions would be counted in the fuel combustion section of this inventory. Finally, the state does not host any large chemical companies of the type that would produce HCFC-22 and emit the ozone-depleting, partially halogenated compound HFC-23 as a by-product (also, HFC-23 was not yet TURA-reportable in 1990).

B. Lime Production

Carbon dioxide is emitted from the manufacture of lime during the calcination process, when the lime is roasted at 2000° F. Lime is manufactured by only two companies in Massachusetts, and their 1990 production figures were not available in printed sources. The production figures used here are from telephone conversations with company representatives. One of the firms produces precipitated calcium carbonate (PCC), also known as quicklime. That process recovers some of the carbon dioxide released by its lime production. However, because the PCC production process is proprietary information, it was not possible to learn how much PCC was produced. In the absence of precise data, an extrapolation from the 1990 national figures provided in the

Workbook (pp. 2-4 and 2-5) was used. Of the 13.7 million tons of CO_2 emitted by lime production nationwide in 1990, 573,000 tons (or 4.1756%) were recovered for use in sugar refining and precipitated calcium carbonate (PCC). That same percentage of recovery was assumed for the Massachusetts data.

Table V-1
1990 Emissions From Lime Production

Lime Production (tons)	CO_2 Factor* (t CO_2/t lime)	CO_2 Emissions (tons)	CO_2 Recovery (%)	CO_2 Recovered (tons)	**Net CO_2 Emissions** (000 tons)
202,179	0.785	158,711	4.1756	6,627	**152**

* From the *Workbook*, pp. 2-4 and 2-5.

C. Limestone Use

Carbon dioxide is emitted from limestone when it is heated as part of several different industrial processes: (a) as flux stone in the chemical and metallurgical industries (e.g., in iron blast furnaces); (b) in flue gas desulfurization systems; and (c) in glass making. Only 9,200 short tons of limestone were consumed in Massachusetts in 1990.[27] The available data do not distinguish between calcite and dolomite for 1990. However, the carbon emissions factor for those two types of limestone are 0.12 and 0.13 tons CO_2/tons lime respectively, and the average of the two is used here: 0.125.

Table V-2
1990 Emissions from Limestone Use

Limestone Use (tons)	Carbon Factor* (t carbon/t lime)	Carbon Emissions (tons)	**CO_2 Emissions** (000 tons)
9,200	0.125	1,150	**4**

* From the *Workbook*, pp. 2-5 and 2-6.

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[27] Source: U.S. Bureau of Mines, *Annual Report, Crushed Stone, 1991.*

VI. LANDFILLS

A. Overview & Discussion

In Massachusetts, as in the U.S. generally, landfills are the single largest anthropogenic source of methane emissions. Landfills are estimated to contribute 195,480 tons of methane per year to the state inventory. This is the equivalent of 4.8 million tons of carbon dioxide emissions.

In general, the decomposition of organic wastes in landfills generates methane over a period of up to 30 years. The actual rate of emissions production varies depending on the quantity and composition of waste in place, soil moisture, and other factors. Since measured data on landfill methane emissions are generally not available, the *Workbook* provides a methodology and certain assumptions that can be used to generate an estimate.

Table VI-1 summarizes estimated 1990 greenhouse gas emissions from municipal and industrial solid waste landfills in Massachusetts.

Table VI-1
1990 Landfill Greenhouse Gas Emissions

Total CH_4 Emissions* (tons)	Flared CH_4 (tons)	Net CH_4 Emissions (tons)	Adjusted CH_4 (90% oxid.)	CO_2-Equivalent Emissions (tons)**	CO_2 from Flaring (tons)	**Total CO_2 Equivalent Emissions** (000 tons)
272,200	55,000	217,200	195,480	4,789,260	151,000	**4,940**

* Includes municipal and industrial solid waste landfills.
** Equals total methane emissions multiplied by a global warming potential of 24.5.

B. Methodology

As a first step it is necessary to know the quantity of waste landfilled in Massachusetts. Unfortunately, the state has only recently begun to keep records of this information. To estimate waste landfilled in Massachusetts over the past 30 years in the absence of better data, state census data were combined with changing per capita landfill waste generation estimates taken from the recent EPA study, *Characterization of Municipal Solid Waste in the United States: 1994 Update* (p. 118). Both population and waste estimates were available in ten-year intervals, i.e., for 1960, 1970, 1980, and 1990. Estimates were made for each year between 1960 and 1990 by making a straight line interpolation of the change from decade to decade. Landfilled waste for each year could

then be obtained by simply multiplying the estimated population by the landfill waste factor (note: this factor is given in pounds per person per day and was multiplied by 365 days for an annual figure). This method yielded a 30-year total for Massachusetts of approximately 80 million tons. (See Appendix E.)

Since the *Workbook* provides for different methodologies to estimate emissions from small vs. large landfills, the next step is to calculate what fraction of waste is in large landfills (defined as having 1.1 million tons of waste or more). Information on landfill size was found in a 1994 study commissioned by the Council of Northeastern Governors (CONEG) on the feasibility of gas recovery and energy production from landfills. At that time, there were approximately 26 large landfills in Massachusetts holding approximately 60 million tons of waste.[28] (Note that this implies a lower fraction of waste disposed to large landfills than the default assumption of 89% given on page 5-4 of the *Workbook*. However, it is consistent with the observation of state solid waste authorities that Massachusetts has a large number of small landfills.)

Once total methane emissions were calculated, using the equations for large and small landfills provided in the *Workbook*, additional calculations were necessary to account for the methane flared at seven of Massachusetts' large landfills, which convert the methane emissions to carbon dioxide emissions. In addition, emissions from non-hazardous industrial waste landfills were estimated by using a default assumption provided in the *Workbook* that industrial landfills produce 7% of the emissions of municipal solid waste landfills on a national average basis. The calculations follow.

[28] SCS Engineers, *Implementation Guide for Landfill Gas Recovery Projects in the Northeast*, 1994 for CONEG Policy Research Center, Inc., Washington DC.

Landfill Methane Calculations:

Base Methane Emissions from Small Landfills:

20×10^6 tons waste x 0.35 ft^3 CH_4/tons waste-day = 7×10^6 ft^3 CH_4/day

Converting volume to tons:

7×10^6 ft^3 CH_4/day x 0.0077 (tons CH_4/yr)/(ft^3/day)=54,000 t CH_4/yr

Base Methane Emissions from Large Landfills:

Average Waste in Place = 60 million tons/26 landfills = 2.3 million tons/landfill

Using the equation given on p. 5-6 of the *Workbook* and the methane generation factor for a non-arid climate yields:

26 landfills x [419,000 + (0.26 ft^3 CH_4/day x 2.3×10^6 tons)]= 26.4 million ft^3 CH_4/day

Converting volume to tons:

26.4 million ft^3 CH_4/day x 0.0077(tons CH_4/yr)/(ft^3/day) = 204,000 tons CH_4/yr

Adjustment for Methane Flared at Seven of the Large Landfills:
Methane emissions are collected and flared at approximately seven of the large landfills. Assuming these landfills were the same size, on average, as other large landfills, overall methane emissions are adjusted as follows:

CH_4 emissions flared = 204,000 x 7/26 = 55,000 tons CH_4/yr
CH_4 emissions after reduction for flaring = 204,000 -55,000 = 149,000 tons CH_4/yr

Total Emissions from Small and Large Landfills:
Adding small and large landfill methane estimates:

54,000 tons CH_4/yr + 149,000 tons CH_4/yr = 203,000 tons CH_4/year.

Emissions from Industrial Landfills:
Methane emissions are also generated from non-hazardous industrial waste landfills. Lacking specific information on industrial waste landfills in Massachusetts, the 7% assumption given in the *Workbook* is applied here to calculate industrial waste methane emissions from the municipal solid waste emissions estimated above.

0.07 x 203,000 tons CH_4/year = 14,200 tons CH_4/year.

Total Emissions, Including Industrial Landfills:

203,000 tons CH_4/year + 14,200 tons CH_4/year = 217,200 tons CH_4/year.

Adjustment for oxidation:

0.90 (from *Workbook*) x 217,200 tons CH_4/year = **195,000 tons CH_4/year.**

Carbon Dioxide Emissions from Methane Flaring at Landfills:
It is assumed that all of the carbon in the flared methane is converted to CO_2. Using the ratio of molecular weights for CO_2 and CH_4 (44 to 16), yields:

44/16 x 55,000 tons/year CH_4 flared = **151,000 tons CO_2/year**

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VII. AGRICULTURAL EMISSIONS

A. Overview & Discussion

Although the Massachusetts economy has shifted away from agriculture over the last 100 years, agriculture remains an important, though relatively small, source of greenhouse gas emissions. In 1990, approximately 680,000 acres of land were used for agricultural purposes in Massachusetts, including both crop and livestock acreage.[29] Within the agricultural sector there are three main sources of greenhouse gas emissions: nitrous oxide (N_2O) emissions from fertilizer use, methane (CH_4) emissions from animal manure, and methane emissions from the digestive systems of domestic animals. Another agricultural source of emissions is the burning of agricultural waste, such as crop residues; however, sufficient information to calculate emissions from this source in Massachusetts was not available.[30] Greenhouse gas emissions from the state's chief agricultural sources are summarized in Table VII-1.

Table VII-1
1990 Agricultural Greenhouse Gas Emissions

Source	CH_4 Emissions* (tons)	N_2O Emissions** (tons)	CO_2-Equivalent Emissions (000 tons)
Domestic Animals	6,892	n/a	169
Manure Management	1,144	n/a	28
Fertilizer/Soil Management	n/a	33	11
TOTAL	**8,036**	**33**	**208**

* Global warming potential (GWP) for methane is 24.5.
** GWP for nitrous oxide is 320.

The following sections present methodology and results for emissions sources in the agricultural sector.

[29] Tennessee Valley Authority, 1993, "New England Agricultural Statistics."
[30] The *Workbook* provides some default assumptions about amount of crop residue typically burned (10% of total crop residues according to p. D11-1) and the residue fraction for different crops (Table D11-1). However residue statistics are only provided for types of crops that are not grown in significant quantity in Massachusetts. Arguably, carbon dioxide emissions from crop burning are reabsorbed by the growth of subsequent crops and therefore do not represent a net addition to the inventory.

B. Methane from Domestic Animals

Although methane is emitted as a natural by-product of the digestive system of animals, emissions vary by species. In general, enteric fermentation in the rumen (fore-stomach) as part of the digestive process of ruminant livestock, such as cattle, produces the largest amount of methane. Cattle represent the largest livestock population in Massachusetts and the largest source of animal methane emissions. However, these emissions have tended to decline over the years as the state's economy has become less agriculturally based. In 1990, methane emissions from domestic animals totaled an estimated 6,892 tons annually.

Different species contribute different amounts of methane, depending upon their digestive process. To calculate emissions, species-specific emission factors were taken from the *Workbook* and multiplied by the relevant number of animals as reported in *New England Agricultural Statistics, 1993.*

Sample Calculation for Emissions from Mature Dairy Cows:

To calculate annual methane emissions, the number of animals is multiplied by the appropriate emissions factor from the *Workbook* (Table 6-1 and 6-2):

30,000 cows x 258.5 lbs CH_4/cow-yr x 1 ton/2000 lbs = **3,878 tons CH_4**

To convert CH_4 to tons CO_2-equivalent, the GWP of 24.5 is used as a multiplier:

3,878 tons x 24.5 = **95,011 tons CO_2-equivalent**

Results are shown in Table VII-2. Dairy and beef cattle contribute the largest share of methane from domestic animals, because of their large populations and large emissions factor. Horses and sheep account for the next largest share.

Table VII-2
1990 Methane Emissions from Domesticated Animals

Animal Type	# Head	Emission Factor (lbs CH_4/head/yr)	Total CH_4 (tons)	CO_2-Equivalent (000 tons)
Dairy Cattle				
0-12 months	12,000	42.9	257	6.3
12 -24 months	10,000	128.5	643	15.8
Mature Cows	30,000	258.5	3878	95.0
Beef Cattle				
0-12 months	3,000	42.2	63	1.5
12-24 months	5,000	140.4	351	8.6
Mature Cows	11,000	135.3	744	18.2
Bulls	2,000	220	220	5.4
Hogs & Pigs	33,000	3.3	55	1.3
Sheep (w/ Lambs)	16,800	17.6	148	3.6
Horses*	25,500	39.6	505	12.4
Goats*	5,000	11	28	0.7
TOTAL			**6,892**	**168.9**

* Statewide figures were not available for horses and goats. Figures were estimated based on inspection reports from a subset of towns.

C. Manure Management

Methane is produced as an end-product of the anaerobic decomposition of livestock manure. Emissions vary, depending on the management system applied. Manure that is managed with a water-based system, for instance, increases the potential for methane production.

Using the animal population in Massachusetts, as well as typical animal mass and the production factor for volatile solids from the *Workbook*, an estimate of the mass of volatile solids produced annually by each animal type was calculated. (For some species, an average of male and female animal mass was used where this breakdown of information was not available.) Maximum methane production capacity, based on total volatile solids, was then calculated using a species-specific emissions factor (from *Workbook* Table 7-11). This maximum figure was then multiplied by a weighted average methane conversion factor that reflected the mix of manure management practices used in Massachusetts.

Sample Calculation for Management of Manure from Dairy Cattle:

First, total pounds of volatile solids (VS) generated from dairy cattle are calculated, using the typical animal mass (TAM) and the manure factor found in the *Workbook* Table 7-10:

30,000 cows x 1345 lbs/cow x 3.65 lbs VS/cow-yr = 147,277,500 lbs VS/yr

To calculate maximum methane potential, the methane production factor from *Workbook* Table 7-11 is used:

147,277,500 lbs VS/yr x 3.84 ft^3 CH_4/lb VS = 565,545,600 ft^3 CH_4/yr

The amount of methane released depends on the mix of manure management systems used. To calculate an average methane conversion factor for the state, the factor for each management system is weighted according to the percent of manure they represent. Default values for the breakdown of manure management systems in Massachusetts are taken from *Workbook* Tables 7-1 through 7-9. Methane conversion factors for different manure management systems are taken from *Workbook* Table 7-12.

For dairy cattle in Massachusetts, the breakdown of manure management systems is as follows:

Management System	% Manure Managed	Conversion Factor
Liquid Slurry	29%	18.1%
Daily Spread	58%	0.2%
Solid Storage	13%	0.9%

The weighted average methane conversion factor =

(0.29 x 0.181) + (0.58 x 0.002) + (0.13 x 0.009) = 0.0548 = 5.48%

Applying this conversion factor to the maximum potential methane emissions from above:

0.0548 x 565,545,600 ft^3 CH_4 = 30,991,899 ft^3 CH_4

Converting cubic feet of methane to tons:

30,991,899 ft^3 CH_4 x 0.0413 lbs/ft^3 CH_4 x 1 ton/2000 lbs = **640 tons CH_4**

Converting to carbon equivalent (using a GWP for methane of 24.5):

640 tons CH_4 x 24.5 = **15,680 tons CO_2-equivalent**

Results of this type of calculation for all major Massachusetts livestock species are shown in Table VII-3.

Table VII-3
1990 Methane Emissions from Manure Management

Animal Type	# Head	Volatile Solids (000 lbs)	Max. CH_4 Emissions (000 tons)	Conversion Factor (%)	CH_4 Emissions (tons)	CO_2-Equivalent (000 tons)
Dairy Cattle	30,000	147,277	565,546	5.48	641	15.7
Other Cattle	13,000	45,461	123,654	0.9	23	0.6
Young Cattle	27,000	27,869	147,429	0.9	27	0.7
Swine	33,000	25,575	15,143	7.53	294	7.2
Caged Layers	110,500	1,702	9,274	18.1	34	0.8
Turkeys	170,000	4,233	20,361	0.975	4	0.1
Sheep	16,800	8,693	50,159	0.934	10	0.2
Goats*	5,000	2,453	6,673	0.9	1	0.02
Horses*	25,500	92,330	488,428	0.9	91	2.2
TOTAL					**1125**	**28**

* Statewide figures were not available for horses and goats. Figures were estimated based on inspection reports from a subset of towns.

Clearly, cattle contribute the largest portion of methane emissions from manure in Massachusetts. The majority of these emissions are from daily spread and liquid slurry manure management practices. The second largest contribution comes from swine (pigs and hogs), followed by horses.

D. Fertilizer Use

Commercial fertilizers are used in the agricultural sector to increase nitrogen availability in the soil. This results in nitrous oxide (N_2O) emissions to the atmosphere. Although these emissions are small relative to carbon dioxide emissions, nitrous oxide has a global warming potential 320 times that of carbon dioxide by weight. As a result, fertilizers are an important consideration in any greenhouse gas inventory.

In Massachusetts, urea is by far the most commonly used fertilizer and accounts for most of the nitrous oxide emissions from agricultural soil management -- a total of 23.7 tons in 1990. The next most common fertilizer types were nitrogen solutions and ammonium nitrate, which contributed 6.6 tons and 2.3 tons of N_2O in 1990, respectively. Collectively, known fertilizer use in Massachusetts contributed 33.4 tons of nitrous oxide, which is equivalent to 10,700 tons of carbon dioxide.

To calculate nitrous oxide emissions, the quantity of different types of fertilizers used in Massachusetts was obtained from the *1993 New England Agricultural Statistics*. A three year average was calculated, using 1990 as a central year, to adjust for year-to-

year fluctuations in fertilizer use due to weather and economic conditions. These amounts were first converted to tons of nitrogen based on the nitrogen content factors provided in the *Workbook* (Table 9-1). Nitrogen content was then multiplied by a coefficient of 0.0117 (as specified in the *Workbook*) to produce a figure for nitrous oxide emissions in units of nitrogen. Finally, to convert to nitrous oxide, nitrogen emissions were multiplied by the molecular weight ratio of N_2O to N (44/28, according to the *Workbook*). Results of these calculations are summarized in Table VII-4.

Table VII-4
N_2O Emissions from Fertilizer Use in Massachusetts

Fertilizer Type	Tons Used (3 yr avg)	N Content (%)	N_2O -N (tons)	Total N_2O Emissions (tons)	CO_2-Equivalent Emissions (000 tons)
Ammonium nitrate	127	33.5	1.49	2.34	0.7
Ammonium sulfate	23	21	0.27	0.42	0.1
Nitrogen solutions	359	35	4.19	6.59	2.1
Sodium nitrate	20	16	0.23	0.36	0.1
Urea	1288	46	15.07	23.68	7.6
TOTAL				**33.39**	**10.7**

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VIII. MUNICIPAL WASTEWATER

A. Overview & Discussion

Methane is produced when the organic material contained in wastewater degrades anaerobically (without oxygen). Treatment conditions affect the amount of methane produced, as does the organic content of the waste. Organic content is measured by the amount of oxygen taken up during decomposition, or biochemical oxygen demand (BOD). Wastewater with a higher BOD will generally produce more methane than wastewater with lower BOD.

In Massachusetts, municipal wastewater treatment makes a small contribution to overall greenhouse gas emissions. Total methane emissions from this source category in 1990 were 4,913 tons, equivalent to 120,369 tons of CO_2 emissions.

B. Methodology

The *Workbook* methodology provided to estimate methane emissions from municipal wastewater in Massachusetts is relatively straightforward. Since state-specific information on BOD generation rates per capita, fraction of waste treated anaerobically, and methane recovery was not available, default values from the *Workbook* were used. The calculation follows:

Calculation for Methane Emissions from Municipal Wastewater:

First, 1990 population is multiplied by a default value to estimate.total BOD generated:

6,016,000 persons x 0.1356 lbs BOD/person-day x 365 days/yr = 298 million lbs BOD/yr

Assuming 15% of the waste is anaerobically treated yields:

0.15 x 298 million lbs/yr = 45 million lbs BOD/yr

Multiplying this figure by a default methane emissions factor yields:

45 million lbs BOD/yr x 0.22 lbs CH_4/lb BOD x 1 ton/2000 lbs = **4,913 tons CH_4**

There is no known methane recovery with wastewater treatment in Massachusetts; hence, this figure represents total emissions. To convert methane emissions to their carbon dioxide equivalent, methane's GWP of 24.5 is used as a multiplier:

4,913 tons CH_4 x 24.5 = **120,369 tons CO_2-equivalent**

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IX. FOREST MANAGEMENT & LAND USE CHANGES

A. Overview & Discussion

Approximately 60% of Massachusetts' land area is classified as forest. The next largest fraction of the state's total land area -- close to 20% -- is classified under residential, commercial/industrial and transportation uses. Massachusetts is not a particularly agricultural state: less than 10% of its area is presently utilized as crop land and pasture. Although forests are prevalent across much of the state, the Commonwealth does not support a large-scale, commercial forest products industry.

Massachusetts' forests represent a net "sink" for greenhouse gas emissions. Carbon is sequestered as growing trees convert carbon dioxide into organic material through the process of photosynthesis. Additional carbon is stored in the organic material that collects in soil and on the forest floor. Overall, total forested acreage in Massachusetts -- and in the Northeast region as a whole -- has increased significantly since the early 1900's. This largely reflects the gradual reversion back to forest of land that was originally cleared for agricultural purposes by European settlers.

More recent state land-use data indicate a small loss of forest as well as crop and pasture acreage, together with a gradual increase in acreage listed as residential, commercial, industrial, or transportation. These land use changes are not dramatic and therefore do not represent a large source of greenhouse gas emissions in the Commonwealth. Between 1971 and 1985, the loss of forest land averaged less than 0.3 percent per year on a state-wide basis; the loss of agricultural land averaged about one quarter of one percent per year; and the increase in land developed for residential, transportation, and commercial/industrial uses averaged about 1.3% per year. Over the same period, there was a small loss of open land, but this was almost fully offset by an increase in urban open land. Land for recreation also increased, as did area classified by the state as "woody perennial," while wetland area stayed basically constant. Figure IX-1 presents a rough breakdown of land uses as a percentage of the state's total area in 1985, the last year for which statewide figures are available. (Appendix F shows land use figures for 1971 and 1985.)

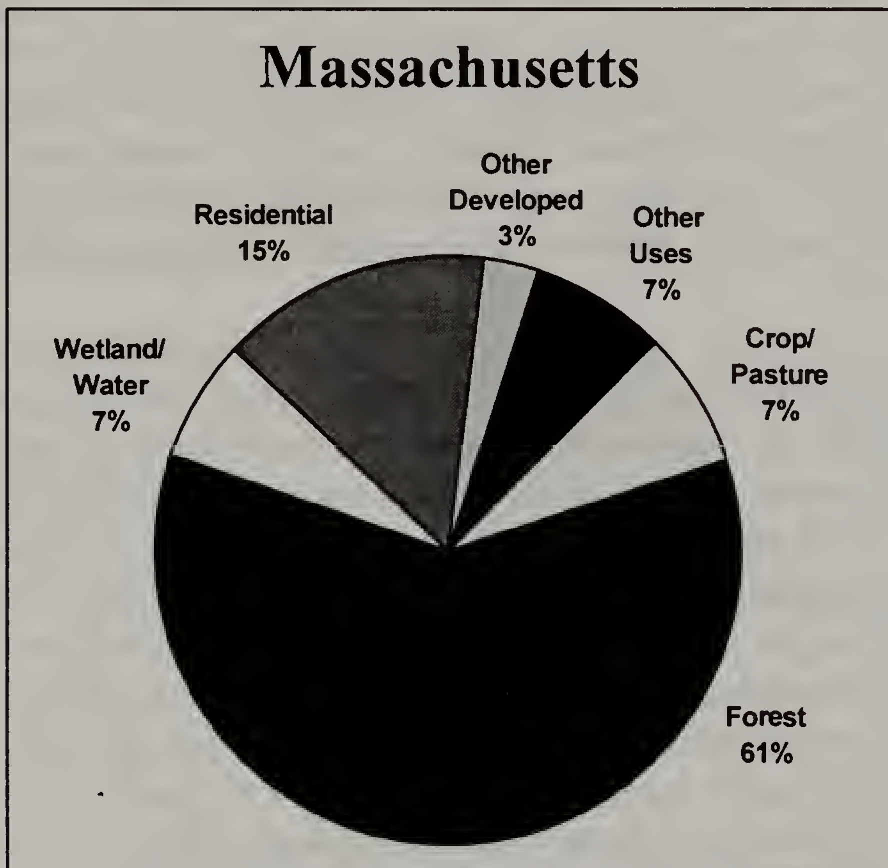
More current data on state-wide land use changes are not available, although some information has been reported for 1990 by selected towns in Massachusetts. This subset, however, was not judged to be adequately representative of state-wide trends because the change in 1971 to 1985 town numbers did not correlate well with the figures for statewide changes in land use over the same period. It was also obvious that the town figures reflected a smaller proportion of agricultural and forest land and a higher proportion of developed land. Hence, it was assumed that a better approximation would be to take the period between 1971 and 1985 as representative of the 25 year average up to 1990.

Aggregating the main land-use categories of interest (see Appendix F), and dividing the total change in acreage between 1971 and 1985 by 14 years, yields the following round figures:

Loss of crop and pasture land:	1,000 acres/year
Loss of forest land:	9,000 acres/year
Gain in "developed" land:	11,000 acres/year

(Note that land-use changes in other categories were considered too small to be of significance for purposes of this calculation.)

Figure IX-1
Land Uses in Massachusetts, 1985



Source: Data Center, MA Executive Office of Environmental Affairs.

Since the gain in "developed" land (i.e., land classified as residential, commercial, industrial, and transportation) slightly exceeded the combined reduction in forest and crop and pasture land, it was further assumed that all loss of forest, crop, and pasture land represented full conversion to residential, industrial, or commercial development. In other words, it was assumed that these changes entailed a total loss of above-ground carbon stocks.

A cautionary note is in order with respect to these assumptions, however. Land use trends between 1971 and 1985 may not be representative of the longer 25-year period before 1990. As noted earlier, the larger trend throughout much of the century has been a

gradual conversion of agricultural land to forest, leading to a net increase in carbon sequestration as a result of land use changes. Conversion to developed uses may not have continued at the same rate after 1985, due to changing economic conditions in Massachusetts that could have effected commercial and residential real estate development. Thus, ten thousand acres per year may not accurately reflect the combined average loss of crop, pasture, and forest land that the state actually experienced in recent decades.

Table IX-1 summarizes the carbon flux associated with land-use changes, forest management, and biomass regeneration patterns characteristic of Massachusetts in recent decades. Note that sequestration is expressed as negative emissions. Overall, carbon sequestration by Massachusetts forests clearly offsets emissions from other land use changes and forest harvesting.

Table IX-1
Approximate Annual Carbon Flux from Biomass Use, Forest Sequestration, and Land Use Change*

	Annual Carbon Emissions (tons)	Annual CO_2 Emissions (000 tons)
Fuelwood Combustion	123,280	452
Forest Harvesting	136,400	500
Land Use Change	646,050	2,369
Forest Sequestration	-3,321,000	-12,177
Urban Tree Planting	-158	-1
TOTAL	**-2,415,428**	**-8,857**

* The negative numbers signify CO_2 *removed* from the atmosphere.

The subsequent sections detail the methodology used and results obtained for each of these categories. Note that no attempt is made to calculate methane or other greenhouse gas emissions from drainage of wetlands because the state land use figures for wetland area stay relatively constant between 1971 and 1985, a trend assumed to continue through 1990.

B. Forest Harvesting

As noted previously, commercial logging is not a significant sector of economic activity in the Commonwealth. About one-quarter of all forest acreage is under management plans. Massachusetts requires that cutting plans must be filed for timber harvests over 25,000 board feet or 50 cords. Each year approximately 23,000-30,000 acres are cut under this requirement. These records show that approximately 50 million board feet were harvested in 1990, in addition to 50,000 cords. However, because a large

number of harvests may fall under the size threshold required to file a plan, these figures undoubtedly understate total forest harvesting.

Unfortunately, no further information is available on smaller scale harvesting that would help to estimate the actual total amount of wood removed from Massachusetts forests in 1990. With that caveat, the following simplifying assumptions were made: (1) all known wood harvests reported in board feet are assumed to be for non-fuel purposes; and (2) all known wood harvests reported in cords are assumed to be for fuelwood purposes. Direct carbon emissions from the fuelwood increment are captured in the first section of the inventory. Thus, for purposes of this section, calculations only included the additional carbon emissions from the 50 million board feet for which cutting plans were filed.

While this approach almost certainly understates carbon emissions, by failing to account for smaller harvests of wood for non-fuel purposes, the difference is not likely to be significant for two reasons. First, most small scale harvesting is likely to be for fuel wood purposes (which is fully captured, from the standpoint of carbon emissions, in Section III). And, second, forest harvesting is unlikely to be a significant source of overall carbon emissions for the state in any case.

Using the assumptions outlined above, forest harvesting in Massachusetts is estimated to yield total annual carbon emissions of 136,400 tons. The calculations follow.

Calculations for Emissions from Forest Harvesting:

To do the carbon emissions calculations, board feet are first converted to cubic feet using a factor of 5.5 board feet per cubic foot:

$$\frac{\text{50 million board feet/yr}}{\text{5.5 board feet/ft}^3} = \text{9.09 million ft}^3\text{/yr}$$

To calculate carbon emissions, default values provided in the *Workbook* are used (dm = dry matter; t = tons):

$$\text{9.09 million ft}^3\text{/yr} \times 0.030 \text{ t dm/ft}^3 \times 0.5 \text{ t C/t dm} = \mathbf{136{,}400 \text{ tons C/yr}}$$

where 0.030 t dm/ft^3 is the combined conversion and expansion ratio for logged forests from the *Workbook*, and the carbon fraction of dry matter is assumed to be 50%.

The above calculation, besides being inexact for the reasons discussed above, does not attempt to address a number of important complexities that effect the actual year to year carbon flux associated with forest harvesting. Depending on how the wood is used, for instance, oxidation of the sequestered carbon could occur over a period of many years. Moreover, most of the wood is probably taken from forests which are allowed to naturally regenerate, meaning that an equivalent amount of carbon will eventually be re-sequestered. This offsetting sequestration is captured in Part D of this section, but the

calculations used are based on broad averages for the regeneration of Massachusetts forests as a whole. Depending on how intensively the logged areas are managed, actual regeneration can occur at significantly different rates in recently harvested forests. Unfortunately, state-specific information on this issue is also lacking. Approximately 20% of the acreage for which cutting permits are filed are under sustainable management plans, but the practical impacts of these plans are unclear.

C. Emissions from Land Use Changes

As noted above, the most recent available land use data suggest that the state gradually lost small amounts of forest, crop, and pasture land to development between 1971 and 1985. For purposes of calculating emissions from land use changes, it was assumed that this trend continued to 1990. However, as discussed previously, economic conditions in the state around that time cast some doubt on the validity of this assumption.

To calculate carbon emissions from land use changes, the round figures cited previously were used:

Loss of crop and pasture land:	1,000 acres/yr
Loss of forest land:	9000 acres/yr

The change in acreage was simply multiplied by an average factor for biomass density (expressed as tons of dry matter per acre) to estimate the change in carbon stocks. For purposes of this calculation, since it was assumed that all loss of agricultural and forest land is to conversion for development, this represents the total biomass assumed to be removed. Once the loss of above-ground carbon stocks was calculated, changes in soil carbon were calculated, again using simple factors provided by the *Workbook* for different land uses, as follows:

Calculations for Carbon Flux from Land-Use Changes:

Aboveground Biomass Density for crop and pasture land, based on default value for agricultural land uses from p. 10-8 of *Workbook* = 4.5 tons dry matter/acre
(*Note:* dm = dry matter, t = tons)

Carbon flux from conversion of 1,000 acres/year of crop and pasture land, assuming that the carbon fraction of dry matter is 50% =

1,000 acres/yr x 4.5 t dm/acre x 0.5 = 2,250 t C/yr

Aboveground Biomass Density for forests depends on forest type. All Massachusetts forests are secondary, having been logged at some point. Approximately 60% of the forests are deciduous, and 40% are evergreen (see Appendix F for a breakdown of Massachusetts forest species). It is assumed that this distribution is also typical of the acreage that was converted. Using default values from *Workbook* Table 10-3:

Deciduous = 60% x 9,000 acres/yr x 78.1 t dm/acre x 0.5 (C fraction) = 210,870 t C/yr

Evergreen = 40% x 9,000 acres/yr x 98.1 t dm/acre x 0.5 (C fraction) = 176,580 t C/yr

Total from forest conversion = 210,870 + 176,580 = 387,450 t C/yr

Total from forest & crop/pasture conversion = 387,450 + 2,250 = **389,700 tons C/yr**

To calculate loss of soil carbon from land use changes, the corrected default values from the *Workbook* (which are the same for deciduous and evergreen forests) are used:

Forest Soil Carbon Loss = 9,000 acres/yr x 53.5 t C/acre = 481,500 t C/yr
Agric. Soil Carbon Loss = 1,000 acres/yr x 31.2 t C/acre = 31,200 t C/yr

Combined Potential Soil Carbon Loss = 481,500 + 31,200 = 512,700 t C/yr

Using the *Workbook*'s default fraction of 50% for carbon released over 25 years yields:

0.5 x 512,700 = **256,350 tons C/yr**

Therefore, total annual carbon emissions associated with land use changes =

389,700 t/yr (above ground carbon) + 256,350 t/yr (soil carbon) = **646,050 tons C/yr**

D. Carbon Sequestration from Regeneration of Forests

Massachusetts' forests create an important sink for carbon emissions, sequestering large amounts of carbon as they grow and add biomass. In general, Massachusetts forests are under 100 years old, which means that they have not reached the biomass density of fully mature systems and that the regeneration factors provided in the corrected Table 10-5 of the *Workbook* can be applied.

Using the breakdown of evergreen and deciduous forest species noted earlier, and taking three million acres as the total forest area for the state, yields the following calculations for carbon uptake:

Calculations for Carbon Sequestration by Massachusetts Forests:

Default values for annual carbon sequestration are taken from corrected *Workbook* Tables 10-5 and 10-6. Again, the carbon fraction of dry matter is assumed to be 50%.
(*Note:* dm = dry matter, t = tons)

Aboveground carbon stocks =

Deciduous = 60% x 3 million acres x 0.89 t dm/yr-acre x 0.5 (C fraction) = 801,000 t C/yr

Evergreen = 40% x 3 million acres x 1.3 t dm/yr-acre x 0.5 (C fraction) = 780,000 t C/yr

Soil carbon stocks = 3 million acres x 0.58 t C/yr = 1,740,000 t C/yr

Total annual aboveground and soil carbon uptake =

801,000 + 780,000 + 1,740,000 = **3,321,000 tons C/yr**

E. Carbon Uptake from Urban Tree Planting:

Carbon is also sequestered by trees planted in urban areas. Unfortunately, reliable figures for the numbers of trees planted annually in Massachusetts are difficult to obtain because a variety of state and civic organizations engage in this activity. The Bureau of Shade Tree Management, the Tree Wardens' and Foresters' Association, and Mass ReLeaf together plant approximately 45,000 trees per year. By comparison, the Massachusetts Association of Conservation Districts distributes approximately a half million seedlings per year. Even the latter figure, however, probably does not capture the total number of seedlings planted state-wide in a typical year. On the other hand, many of the new seedlings are undoubtedly being planted to replace existing trees that have either died or been cleared for some reason. Hence, for purposes of calculating carbon uptake from urban tree planting, the more conservative figure of 45,000 trees planted per year were used. This would result in approximately 293 tons of annual average carbon uptake.

Calculation for Carbon Uptake from Urban Tree Planting:

The *Workbook* does not provide annual regeneration rates for individual trees. The Massachusetts Department of Environmental Management provided a figure of 7 lbs C/year-tree for the annual rate of carbon fixation for an average, mature tree. (The actual figure varies depending on the species and is probably higher for newly planted seedlings and young trees.) This yields:

45,000 trees x 7 lbs C/year-tree x 1 ton/2000 lbs = **158 tons C/yr.**

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X. PROJECTED YEAR 2000 EMISSIONS

In this section carbon dioxide emissions from Massachusetts energy use are projected for the year 2000, the benchmark date for stabilizing national greenhouse gas emissions under current Administration policy. These projections are based on forecasts of future energy use generated by DOER using the SAFER model (see Appendix A). Emissions of greenhouse gases other than carbon dioxide are not projected, nor are emissions from non-energy sources of greenhouse gases, such as agriculture and land-use change. This is because reliable forecasts for non-energy sources and non-carbon dioxide emissions are generally not available.

In terms of forecasting future emissions trends, however, this approach yields a relatively complete picture, both because energy-related carbon dioxide emissions overwhelmingly dominate the state inventory in any case (accounting for 95% of the overall total shown in Table II-2, including electricity imports and upstream emissions), and because non-energy sectors such as land-use and agriculture are not expected to change their contributions dramatically between 1990 and 2000. Table X-1 compares actual 1990 and projected 2000 carbon dioxide emissions by primary energy use sector in Massachusetts. Overall, current forecasts project an 11.1% increase in energy-related carbon dioxide emissions between 1990 and 2000. By far the largest increase, both on a percentage basis and in terms of absolute emissions, is projected to occur in the transportation sector, which accounts for fully two-thirds of the overall increase projected to occur by 2000 (see Figure X-1).

Table X-1
Projected Year 2000 CO_2 Emissions from Primary Energy Use*
(in thousands of tons)

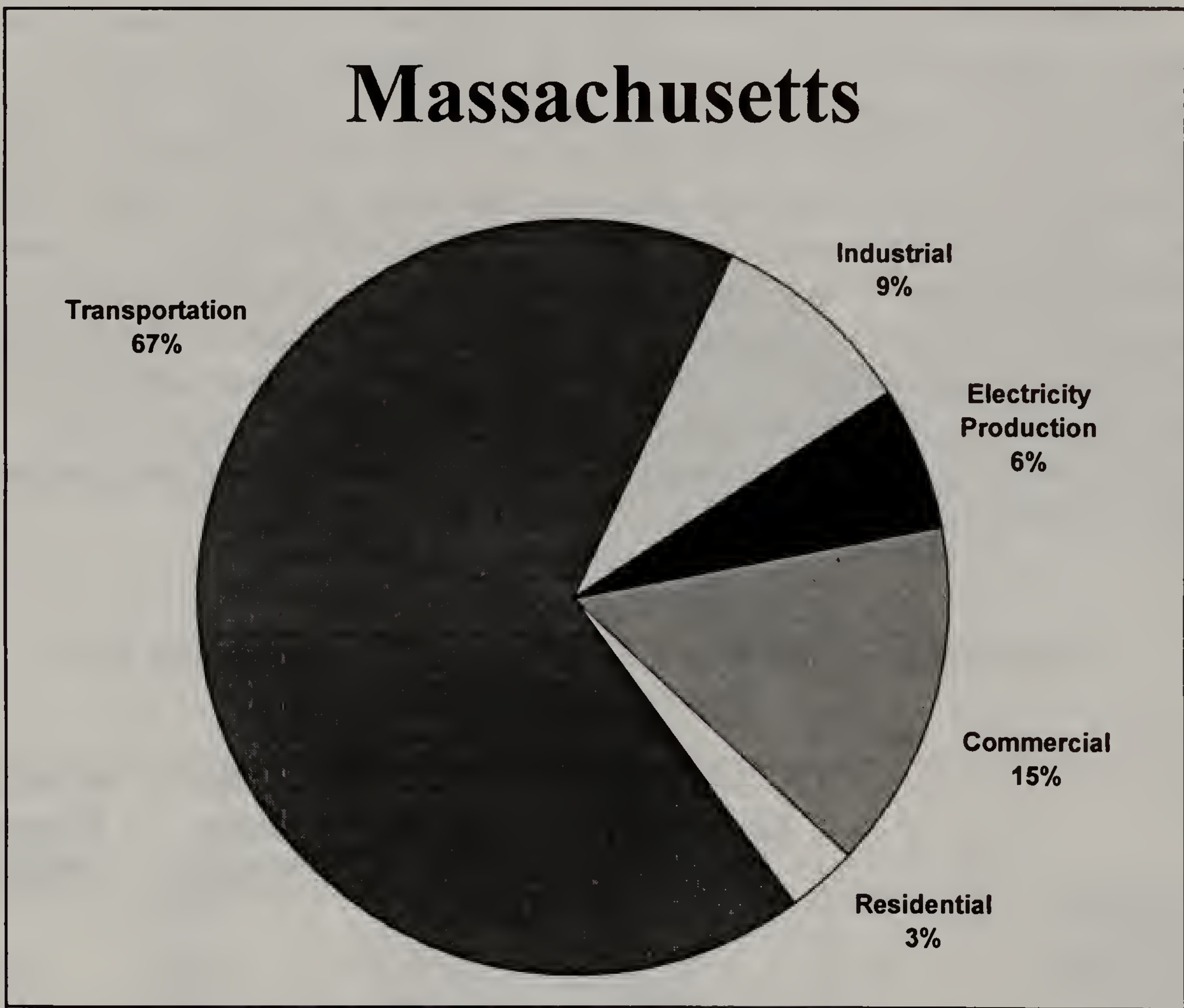
	1990 Emissions (actual)	**2000 Emissions** (projected)	**Projected Increase, 1990-2000**	**Percentage Change, 1990-2000**
Residential	14,326	14,659	333	+ 2.3%
Commercial	9,902	11,343	1,441	+14.6%
Industrial	4,872	5,750	878	+18.0%
Transportation	31,436	38,076	6,640	+21.1%
Electricity Production**	28,554	29,192	638	+ 2.2%
TOTAL	**89,090**	**99,020**	**9,930**	**+11.1%**

* Does not include emissions from wood combustion or upstream fuel-cycle emissions. Projected electricity emissions are not apportioned by end-use sector.
** Electricity Production includes net electricity imports.

The commercial and industrial sectors are similarly expected to experience substantial emissions growth, although the increases, in absolute and percentage terms,

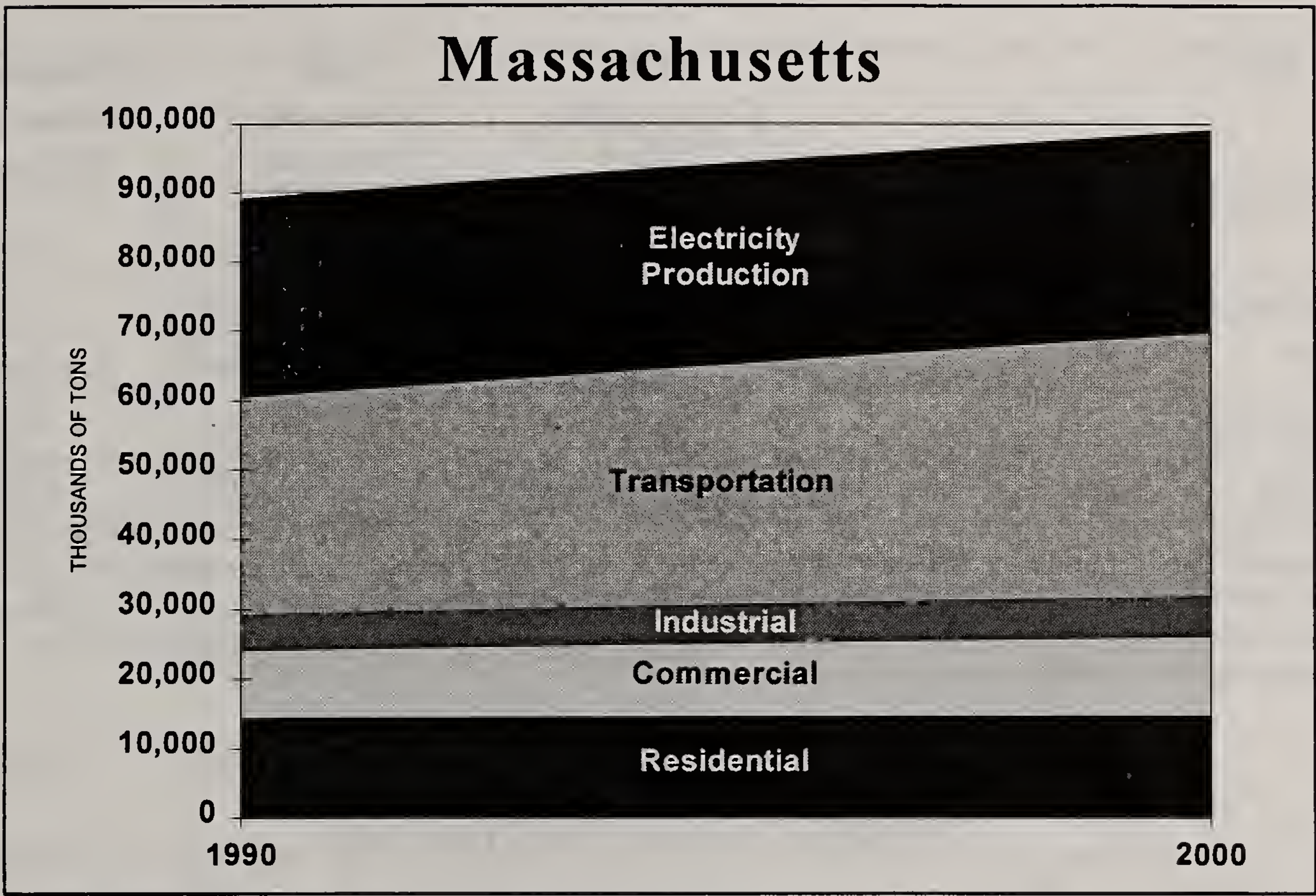
are smaller. In the commercial sector, fuel switching to natural gas plays a role in dampening emissions increases. The overall carbon dioxide increase is projected to be less than 15% despite the fact that primary energy consumption in this sector is expected to increase by 19%. In the industrial sector, by contrast, natural gas use is expected to stay constant, with most of the projected emissions increase coming from increased use of residual and heating oil, motor gasoline, and miscellaneous petroleum products. Figure X-2 shows the trend line (omitting year-to-year fluctuations) in carbon dioxide emissions between 1990 and 2000 for the primary energy use sectors.

Figure X-1
Shares of Total Projected CO_2 Emissions Increase, 1990-2000



Source: DOER SAFER Model (via MA Inventory, Table X-1).

Figure X-2
1990-2000 Projected CO_2 Emissions from Primary Energy Consumption*



Source: DOER SAFER Model (via MA Inventory, Table X-1).
* It should be noted that year-to year fluctuations are not indicated on this graph.

Fuel switching to natural gas clearly plays a major role in holding down emissions in the residential and electricity production sectors, which stand out for their relatively low emissions growth between 1990 and 2000. Because natural gas is an inherently less carbon-intensive fuel than petroleum or coal, greater use of natural gas tends to dampen carbon dioxide increases despite continued growth in energy consumption. In the electricity production sector, for instance, natural gas use is projected to increase by 87% between 1900 and 2000, while oil use declines by 10% and coal use declines by almost 8%. In addition, Massachusetts expects to purchase large amounts of hydro-electric power over the course of the decade. As a result, the overall carbon dioxide emissions increase projected for electricity production over the 1990-2000 period is just 2.2%.[31] In the residential sector, fuel oil use is expected to decline by 12% during the 1990-2000 period, while natural gas use increases by 23%. Table X-2 compares the changing fuel mix used to meet Massachusetts energy needs between 1990 and 2000, and this is shown graphically in Figure X-3.

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[31] Note, however, that the SAFER projections assume nuclear power plants will operate to the end of their license periods. Recent developments in the electric power industry cast some doubt on this assumption. If nuclear plants are retired early and are replaced by fossil fuel-powered generating capacity, growth in carbon dioxide emissions from this sector could significantly exceed current projections.

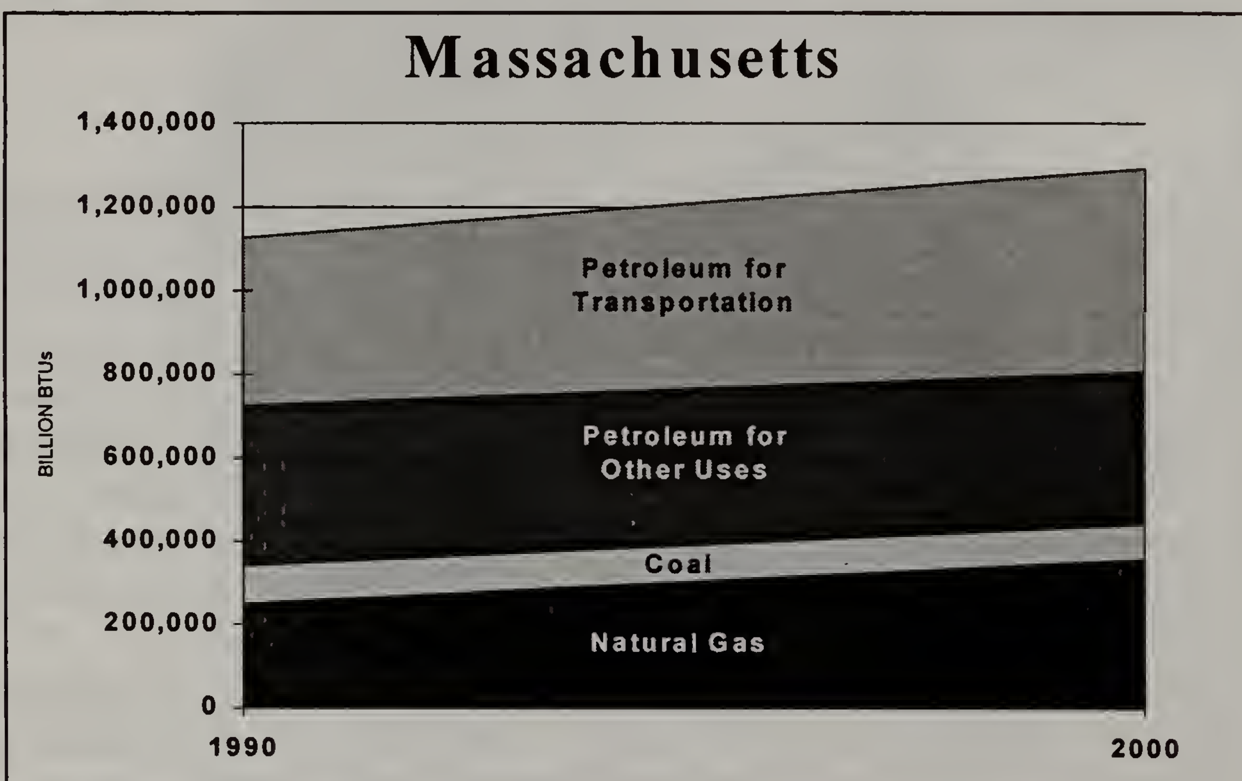
Table X-2
Projected Year 2000 Energy Consumption by Fuel*
(million Btu)

Fuel Type	**1990 Consumption** (actual)	**2000 Consumption** (projected)	**Projected Percentage Change**
Petroleum Products for Transportation Uses	401,528,000	484,989,000	+20.8%
Petroleum Products for Other Uses	385,916,000	366,001,000	- 5.2%
Coal**	89,963,000	84,263,800	- 6.3%
Natural Gas	250,255,000	357,810,000	+43.0%
TOTAL	**1,127,662,000**	**1,293,063,800**	**+14.7%**

* Includes net electricity imports for which fuel source is identified. Bulk electricity purchases from the regional power pool (which are not included here because their precise fuel sources are not known) are projected to decline slightly between 1990 and 2000, from 5,649,400 MWH to 5,426,600 MWH.

** Coal consumption figures account for the fact that a significant portion of coal-generated electricity from Massachusetts is exported out of state.

Figure X-3
1990-2000 Projected Fossil Fuel Mix*



Source: DOER SAFER Model (via MA Inventory, Table X-2).
* It should be noted that year-to-year fluctuations are not indicated on this graph.

In sum, absent further policy actions to reduce emissions, the Massachusetts carbon dioxide inventory can be expected to grow significantly, driven in large part by continued growth in energy use by the transportation sector. To return projected year 2000 emissions to 1990 levels, Massachusetts would have to reduce overall carbon dioxide emissions by approximately 10 million tons.

APPENDICES

APPENDIX A

The SAFER Model

Appendix A

The SAFER Model

SAFER is the State Annual Forecast of Energy Resources, a computer model that was developed by the Massachusetts Division of Energy Resources to forecast and analyze energy needs for Massachusetts. It is used to develop and test scenarios of the state's energy future. The SAFER project is designed to perform medium-to-long-range energy policy analysis.

The SAFER project has been utilized by this greenhouse gas inventory to estimate energy use in Massachusetts. These estimates have then been used to calculate the amount of CO_2 produced in the consumption of this energy.

Future economic growth estimates are the most important assumptions in the model. This is because the demand for energy is derived from the demand for goods and services. SAFER obtains its assumptions about economic activity for each future year from Regional Economic Models Incorporated (REMI). REMI's estimates of economic activity are based in part on the energy prices and demands of the previous year.

In 1994 dollars, REMI forecasts the Massachusetts' Gross State Product to grow from $168 billion in 1990 to $203 billion by the year 2000. It is more meaningful to examine changes in using constant 1994 dollars, as this factors out inflation. Thus, the economy is expected to grow over 20% in real terms during the decade ending in the year 2000. Putting this in perspective, if energy were used at the same rate per dollar of output in the year 2000 as in 1990, then 20% more energy would be needed in the year 2000.

All forecasting is subject to uncertainties and energy forecasting is particularly so because it relies on forecasts of so many other factors. Energy is not demanded for itself, but for what it can do. People do not want electricity, natural gas, oil or gasoline, per se. Rather, they want hot water, heat, and light for their homes and offices, motorized transportation from one place to another, and factory machinery churning out products. Therefore, energy demand is often referred to as a "derived" demand, meaning that the demand for it is driven by the level of activity in the economy and how energy is used to fuel this activity. Consequently, forecasts of economic activity, fuel prices, and expected changes in the process efficiency of energy using devices are all variables that impact future energy demand. Errors in any of these factors can be compounded in developing an energy forecast.

An important set of inputs to the model is the projected price of each fuel available for use in Massachusetts. Since Massachusetts has no significant influence over these prices, they are input to the model exogenously, based on U. S. Department of

Energy (DOE) price forecasts, adjusted for Massachusetts delivery costs. The "well head" or "mine-mouth" prices for primary fuels are forecasted by the DOE's Energy Information Administration (EIA). It should be noted that the real (inflation adjusted) prices for petroleum and coal are expected to be lower in the year 2000 than they were in 1990 (recall the 1990's prices were boosted by the Gulf War). The real price forecast used in the estimating the changes in year 2000 energy demand compared to 1990 levels were as follows:

- Petroleum prices decrease by 21%;
- Coal prices decrease by 15%; and
- Natural Gas prices increase by 14%.

Along with these future trends, the SAFER model is driven by detailed historical data. This includes the historical relationships of the pattern of energy consumption for each end use and other factors in the model. Using these assumptions and formulas, SAFER estimates the future consumption of every energy resource for the following sectors:

- Residential
- Commercial
- Industrial
- Transportation
- Electricity
- Natural Gas

The SAFER model is based on the Energy 2020 model. Energy 2020 is a system dynamics based model that takes into account the interactive nature of the "feedback loops" between energy demand, prices and supply. The focus of system dynamics methodology is to accurately describe the linkages in a system. In SAFER's case, the system is energy supply and demand in Massachusetts. Energy 2020 evolved from the US DOE Fossil2 model, and it is used widely throughout the U.S. and Canada by both utilities and government agencies for energy planning.

APPENDIX B

Worksheets to Calculate 1990 CO_2 Emissions from Fossil & Biomass Fuels

TABLE 1	1990 Residential Sector CO_2 Emissions
TABLE 2	1990 Commercial Sector CO_2 Emissions
TABLE 3	1990 Industrial Sector CO_2 Emissions
TABLE 3a	Calculation of Carbon Stored by Non-Fuel Use in the Industrial Sector in 1990
TABLE 4	1990 Transportation Sector CO_2 Emissions
TABLE 5	Total 1990 Electric Utility CO_2 Emissions -- In-State & Net Imported
TABLE 5a	1990 In-State Electric Utility CO_2 Emissions
TABLE 5b	1990 Net Imported Electricity CO_2 Emissions

Worksheets to Calculate CO_2 Emissions from Fossil & Biomass Fuels

Notes

Column 1 Fuel uses are from historical data in DOER's 1993 SAFER Forecast. End uses within coal and oil categories are based on percentage uses reported in SEDS. Wood use is expressed in tons per year, not mmBtu's.

Column 1b Table 3a only. The fraction used for non-fuel is calculated from U.S. averages using the EIA Annual Energy Review, Table 1-15, and U.S. consumption estimates in SEDS.

Column 1c Table 3a only. = (1) x (1B).

Column 2 Coefficients are from the EPA *Workbook*. The coefficient for wood is expressed in percentage of carbon content by weight.

Column 2a Table 3a only. = (2) x (2B).

Column 2b Table 3a only. Source: EPA *Workbook*, Table D1-3.

Column 3 = (1) x (2)/2000, except that the calculation for wood = (1) x (2).

Column 4 Table 3 only. "Stored Carbon" is calculated in Table 3a and is netted out of the calculation of carbon for the industrial sector (Table 3, Column 6).

Column 5 "International Bunker" consists of fuels used in international transportation, which is not applicable in Massachusetts.

Column 6 (6) = (3) except in Table 3, where Net Carbon = (3) - (4) - (5).

Column 7 Percentage of carbon released in combustion is from the EPA *Workbook*, pp. D-1-10.

Column 8 = (6) x (7). This is the same as (3) x (7) except in Table 3.

Column 9 = (8) x (44/12). The molecular weight of carbon = 12, of CO_2 = 44.

Wood* Wood consumption figures are given in tons, not mmBtu's, and carbon content is expressed as a percentage by weight. Available wood data did not disaggregate the commercial and industrial sectors; all of the small amount consumed is here attributed to the industrial sector. Wood figures are not included in the Totals.

Bituminous Coal** Tables 5, 5a, and 5b only. A portion of the electricity from coal-burning power plants located in Massachusetts serves customers in other states. This is reflected in the negative net import figure (Table 5b), and in the fact that in-state emissions from coal (Table 5a) are higher than total (net) emissions from coal (Table 5).

System Purchases*** Tables 5 and 5b only. "System purchases" are imports whose fuel type is unknown. These totaled 5,649.400 MWH in 1990. NEPOOL estimates its 1990 average CO_2 emission rate at 0.49 tons per MWH (*NEPOOL Generation Emissions Analysis; Summary Report*, December 1995, p. 110). Using this system-wide average, DOER estimates that system purchases contributed 2,768,206 tons of CO_2.

APPENDIX B
Table 1
1990 Residential Sector CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5		N/A	N/A	Same as 3	99%		
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	100,696,000	44.0	2,215,312				99%	2,193,159	8,041,583
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	900,000	43.5	19,575				99%	19,379	71,057
LPG	4,899,000	37.8	92,591				99%	91,665	336,106
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil		47.4							
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal	400,000	62.1	12,420				99%	12,296	45,085
Bituminous Coal	300,000	56.0	8,400				99%	8,316	30,492
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	99,700,000	31.9	1,590,215				99.5%	1,582,264	5,801,634
Wood*	220,000 t	47.5%	104,500				90%	94,050	344,850
Ethanol		41.8							
TOTAL [w/o wood]	**206,895,000**		**3,938,513**					**3,907,079**	**14,325,956**

Source: DOER SAFER Model

APPENDIX B
TABLE 2
1990 Commercial Sector CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5				Same as 3	99%		
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	41,028,000	44.0	902,616				99%	893,590	3,276,496
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	791,000	43.5	17,204				99%	17,032	62,451
LPG	1,017,000	37.8	19,221				99%	19,029	69,773
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline	452,000	42.8	9,673				99%	9,576	35,112
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	32,212,000	47.4	763,424				99%	755,790	2,771,231
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal	300,000	62.1	9,315				99%	9,222	33,813
Bituminous Coal	500,000	56.0	14,000				99%	13,860	50,820
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	61,900,000	31.9	987,305				99.5%	982,368	3,602,018
Wood*		47.5%							
Ethanol		41.8							
TOTAL	**138,200,000**		**2,722,759**					**2,700,468**	**9,901,715**

Source: DOER SAFER Model

APPENDIX B
TABLE 3
1990 Industrial Sector CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil	7,542,000	45.5	171,581	159,741		11,839	99%	11,721	42,976
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	10,763,000	44.0	236,786	10,419		226,367	99%	224,104	821,714
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	85,000	43.5	1,849	81		1,767	99%	1,750	6,416
LPG	2,966,000	37.8	56,057	43,231		12,826	99%	12,698	46,558
Lubricants	1,949,000	44.6	43,463	21,731		21,731	99%	21,514	78,885
Misc. Petroleum Products	10,763,000	44.7	240,553	10,584		229,969	99%	227,669	834,786
Motor Gasoline	1,864,000	42.8	39,980	0		39,890	99%	39,491	144,799
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	14,068,000	47.4	333,412	14,670		318,741	99%	315,554	1,157,032
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal	100,000	62.1	3,105	19		3,086	99%	3,056	11,204
Bituminous Coal	1,700,000	56.0	47,600	286		47,314	99%	46,841	171,751
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	28,600,000	31.9	456,170	29,651		426,519	99.5%	424,386	1,556,083
Wood*	64,000 t	47.5%	30,400	0		30,400	90%	27,360	100,320
Ethanol		41.8							
TOTAL [w/o wood]	**80,400,000**		**1,630,465**	**290,414**		**1,340,051**		**1,328,783**	**4,872,203**

Source: DOER SAFER Model

APPENDIX B
TABLE 3a
Calculation of Carbon Stored by Non-Fuel Use in the Industrial Sector in 1990

	1 Consumption (mmBtu)	1A % Used as Non-Fuel	1B Non-Fuel Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	2A Gross Total Non-Fuel Use Carbon Stored (tons)	2B Fraction of Non-Fuel Use Stored	4 Stored Carbon (tons)
Asphalt and Road Oil	7,542,000	93.1%	7,021,602	45.5	159,741	100%	**159,741**
Aviation Gasoline				41.6			
Distillate Fuel Oil (Heating Oil)	10,763,000	4.4%	473,572	44.0	10,419	100%	**10,419**
Jet Fuel: Kerosene Type				43.5			
Jet Fuel: Naphtha Type				43.5			
Kerosene	85,000	4.4%	3,740	43.5	81	100%	**81**
LPG	2,966,000	96.4%	2,859,224	37.8	54,039	80%	**43,231**
Lubricants	1,949,000	100.0%	1,949,999	44.6	43,463	50%	**21,731**
Misc. Petroleum Products	10,763,000	4.4%	473,572	44.7	10,584	100%	**10,584**
Motor Gasoline	1,864,000	0%	0	42.8	0	n/a	**0**
Naphtha (<104° Fahrenheit)				40.0			
Naphtha (>104° Fahrenheit)				44.0			
Pentane Plus				40.2			
Petroleum Coke				61.4			
Residual Fuel Oil	14,068,000	4.4%	618,992	47.4	14,670	100%	**14,670**
Still Gas				38.6			
Waxes				43.7			
Anthracite Coal	100,000	0.8%	800	62.1	25	75%	**19**
Bituminous Coal	1,700,000	0.8%	13,600	56.0	381	75%	**286**
Sub-bituminous Coal				57.9			
Lignite Coal				58.7			
Coke							
Natural Gas	28,600,000	6.5%	1,859,000	31.9	29,651	100%	**29,651**
Wood*	64,000 t	0%	0	47.5%	0	n/a	**0**
Ethanol				41.8			
TOTAL [w/o wood]	**80,400,000**		**15,273,102**		**323,055**		**290,414**

Source: DOER SAFER Model

APPENDIX B
TABLE 4
1990 Transportation Sector CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5					99%		
Aviation Gasoline	500,000	41.6	10,400			10,400	99%	10,296	37,752
Distillate Fuel Oil (Heating Oil)	43,692,000	44.0	961,224			961,224	99%	951,612	3,489,243
Jet Fuel: Kerosene Type	55,490,000	43.5	1,206,908			1,206,908	99%	1,194,838	4,381,074
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG	200,000	37.8	3,780			3,780	99%	3,742	13,721
Lubricants	2,899,000	44.6	64,648			64,648	99%	64,001	234,671
Misc. Petroleum Products		44.7							
Motor Gasoline	290,049,000	42.8	6,207,049			6,207,049	99%	6,144,978	22,531,586
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	8,698,000	47.4	206,143			206,143	99%	204,081	748,298
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal		56.0							
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas		31.9							
Wood*		47.5%							
Ethanol		41.8							
TOTAL	**401,528,000**		**8,660,150**			**8,660,150**		**8,573,549**	**31,436,346**

Source: DOER SAFER Model

APPENDIX B
TABLE 5
Total 1990 Electric Utility CO_2 Emissions -- In-State & Net Imported

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5							
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	2,800,000	44.0	61,600			61,600	99%	60,984	223,608
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG		37.8							
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	154,121,000	47.4	3,652,668			3,652,668	99%	3,616,141	13,259,184
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal**	86,663,000	56.0	2,426,564			2,426,564	99%	2,402,298	8,808,427
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	60,055,000	31.9	957,877			957,877	99.5%	953,088	3,494,656
Wood*		47.5%							
Ethanol		41.8							
Electric Utility Subtotal	303,639,000		7,098,709			7,098,709		7,032,511	25,785,875
System Purchases***									2,768,206
TOTAL ELECTRIC UTILITY									**28,554,081**

Source: DOER SAFER Model

APPENDIX B
TABLE 5a
1990 In-State Electric Utility CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5							
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	2,800,000	44.0	61,600			61,600	99%	60,984	223,608
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG		37.8							
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	147,800,000	47.4	3,502,860			3,502,860	99%	3,467,831	12,715,382
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal**	109,700,000	56.0	3,071,600			3,071,600	99%	3,040,884	11,149,908
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	58,100,000	31.9	926,695			926,695	99.5%	922,062	3,380,892
Wood*		47.5%							
Ethanol		41.8							
In-State Electric Utility Total	**318,400,000**		**7,562,755**			**7,562,755**		**7,491,761**	**27,469,790**

Source: SEDS Data

APPENDIX B
TABLE 5b
1990 Net Imported Electricity CO_2 Emissions

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5							
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)		44.0							
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG		37.8							
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	6,321,000	47.4	149,808			149,808	99%	148,310	543,802
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal**	(23,037,000)	56.0	(645,036)			(645,036)	99%	(638,586)	(2,341,481)
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	1,955,000	31.9	31,182			31,182	99.5%	31,026	113,763
Wood*		47.5%							
Ethanol		41.8							
Net Electricity Imports Subtotal	(14,761,000)		(464,046)			(464,046)		(459,250)	(1,683,915)
System Purchases***									2,768,206
Net Electricity Imports Total									**1,084,291**

Source: DOER SAFER 1990 Data, minus 1990 SEDS Data

APPENDIX C

Data Table for 1990 Methane (CH_2) and Nitrous Oxide (N_2O) Emissions from Fuel Combustion

Data Table for 1990 Methane (CH_2) and Nitrous Oxide (N_2O) Emissions from Fuel Combustion

Notes

NB: All figures in this table are for in-state emissions only. Emissions from electricity imports and the upstream fuel cycle are not included here.

* Combustion figures are from DOER's SAFER Model (see Appendices A and B).

** Emissions factors were taken from Sections D13 and D14 of the EPA *Workbook.* To be conservative, early 3-way catalyst (rather than advanced catalyst) control levels were assumed for light cars and trucks.

*** CO_2 equivalents were generated by multiplying CH_4 and N_20 emissions by GWP's of 24.5 and 320, respectively.

**** This assumes that all wood stove use was for residential wood consumption. This overstates CH_4 emissions, since some use was for fireplaces, which don't have CH_4 emissions factor, according to the *Workbook.*

***** This does not include distillate oil or miscellaneous petroleum products for which emissions factors were not available.

APPENDIX C

Data Table for 1990 Methane (CH_2) and Nitrous Oxide (N_2O) Emissions from Fuel Combustion

SECTOR/Fuel	CONSUMP-TION* (mm/Btu)	CH_4 Factor** (lbs/mmBtu)	N_2O Factor** (lbs/mmBtu)	CH_4 Emissions (tons)	N_2O Emissions (tons)	CO_2 Equivalent*** (000 tons)
RESIDENTIAL						0
Distillate Oil	100,696,000	0.011	0	554	0	14
LPG	4,899,000	0.0024	0	6	0	0
Coal	800,000	0	0	0	0	0
Natural Gas	99,700,000	0.0021	0	105	0	3
Wood****	3,960,000	0.164	0	325	0	8
Residential Subtotal				989	0	24
COMMERCIAL						0
Distillate Oil	41,028,000	0.0013	0.035	27	718	230
Residual Oil	32,212,000	0.0035	0.103	56	1659	532
LPG	1,017,000	0.0024	0	1	0	0
Coal	800,000	0.0221	0.131	9	52	17
Natural Gas	61,900,000	0.0025	0.005	77	155	51
Commercial Subtotal				170	2584	831
INDUSTRIAL						0
Residual Oil*****	14,068,000	0.0064	0	45	0	1
Coal	1,800,000	0.0053	0	5	0	0
Natural Gas	28,600,000	0.0029	0	41	0	1
Wood	1,152,000	0.0331	0	19	0	0
Industrial Subtotal				110	0	3
ELECTRIC UTILITY						0
Distillate Oil	2,800,000	0.00007	0	0	0	0
Residual Oil	147,800,000	0.0015	0	111	0	3
Coal	109,700,000	0.0013	0.0018	71	99	33
Natural Gas	58,100,000	0.0124	0	360	0	9
Wood	78,660	0.0398	0	2	0	0
MSW	19,060,000	0	0	0	0	0
Electric Utility Subtotal				544	99	45
Stationary Total				1814	2683	903
TRANSPORTATION						
Gasoline (light trucks)	96,683,000	0.032	0.029	1547	1402	487
Gasoline (cars)	193,366,000	0.025	0.029	2417	2804	956
Diesel (heavy duty)	43,692,000	0.022	0.004	481	87	40
Jet Fuel	55,490,000	0.0044	0	122	0	3
Aviation Gasoline	500,000	0.133	0.002	33	0	0
Mobile Total				4600	4294	1487
TOTAL				**6414**	**6977**	**2390**

NOTE: All footnotes are on the preceding page.

APPENDIX D

Upstream Fuel Cycle Emissions Factors

Appendix D

Upstream Fuel Cycle Emissions Factors

Fuel Type	CO_2-Equivalent Emissions Factor* (g/mmBtu)	CO_2-Equivalent Emissions Factor** (lbs/mmBtu)
Gasoline***	21,238	46.82
Diesel	15,964	35.19
Fuel Oil	15,474	34.11
Coal	9,060	19.97
Natural Gas	11,115	24.50
Nuclear	14,566	32.11

* From DeLuchi, Mark, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, 1991, Argonne National Laboratory. The DeLuchi factors include emissions from natural gas wells, gas leaks/flares, feedstock recovery, feedstock transport, fuel production, fuel distribution, and compression or liquefaction, where applicable. Non-CO_2 emissions are converted to CO_2-equivalents using global warming potentials for a 100 year time horizon.

** To convert to an emissions factor in lbs/mmBtu, the figure in the second column is multiplied by 2.2046 lbs/1000 grams. The resulting emissions factor in the third column is carried over to Table IV-1 in the text.

*** DeLuchi provides emissions factors for both standard and reformulated gasoline. Standard gasoline is assumed for purposes of this inventory.

APPENDIX E

Data for Calculating Methane (CH_4) Emissions from Landfills

Appendix E

Data for Calculating Methane (CH_4) Emissions from Landfills

The table below provides Massachusetts population figures and average national landfill waste factors for the years 1960, 1970, 1980 and 1990.[1] A straight-line interpolation was used to generate yearly figures as shown on the next page. United States Census data giving yearly population were available for the years 1985-1990 and were used instead of making an interpolation.

	1960	1970	1980	1990
MA Population (in thousands)	5,018	5,689	5,737	6,016
Discards to Landfills (lbs per person per day)	1.67	2.37	2.97	2.93

The EPA *Workbook* gives a default per capita waste generation rate of 4 to 5 lbs/person/day of which 70%, on average, is landfilled (see page 5-2). This yields a landfill discard rate of 2.8 to 3.5 lbs/person/day, roughly consistent with the more recent (1980-1990) factors shown in the table above. It appears that the *Workbook* default value does not take into account a lower rate of waste generation in the 1960's and 1970's.

The table on the next page shows yearly estimated landfilled waste using an interpolation of the figures shown above. The 30-year total shown (81,666,453) was rounded down to 80 million tons for purposes of the calculations shown in Section VI.B of the Inventory.

An example of interpolation:

The known landfill waste factor in 1960 is 1.67 lbs/person/day.
The known landfill waste factor in 1970 is 2.37 lbs/person/day.

To estimate the landfill waste factor in 1965 using a straight-line interpolation we first calculate the average yearly change in landfill waste factors over the 10 years between 1960 and 1970:

(2.37-1.67)/10 years = 0.07/year.

Then the estimated factor in 1965, 5 years after 1960 =

1.67 + (0.07/year x 5 years) = **2.02 lbs of waste per person per day**

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[1] From U.S. EPA, *Characterization of Municipal Solid Waste in the United States: 1994 Update.* EPA530-R-94-042, November, 1994. (Table 36, page 118)

Calculation of Estimated Landfilled Waste

Year	Population	Waste Factor (lbs/pers/day)	Amount Landfilled (tons/yr)
1960	5,018,000	1.67	1,529,361
1961	5,081,377	1.74	1,613,591
1962	5,145,555	1.81	1,699,706
1963	5,210,543	1.88	1,787,737
1964	5,276,353	1.95	1,877,722
1965	5,342,993	2.02	1,969,694
1966	5,410,475	2.09	2,063,690
1967	5,478,809	2.16	2,159,747
1968	5,548,007	2.23	2,257,900
1969	5,618,078	2.30	2,358,188
1970	5,689,000	2.37	2,460,635
1971	5,693,779	2.43	2,525,049
1972	5,698,562	2.49	2,589,569
1973	5,703,348	2.55	2,654,196
1974	5,708,139	2.61	2,718,929
1975	5,712,934	2.67	2,783,770
1976	5,717,733	2.73	2,848,717
1977	5,722,536	2.79	2,913,772
1978	5,727,343	2.85	2,978,934
1979	5,732,154	2.91	3,044,203
1980	5,737,000	2.97	3,109,597
1981	5,765,513	2.97	3,120,843
1982	5,794,167	2.96	3,132,124
1983	5,822,965	2.96	3,143,440
1984	5,851,905	2.95	3,154,791
1985	5,881,000	2.95	3,166,183
1986	5,903,000	2.95	3,173,718
1987	5,935,000	2.94	3,186,591
1988	5,980,000	2.94	3,206,386
1989	6,015,000	2.93	3,220,762
1990	6,016,000	2.93	3,216,906
Total			**81,666,453**

APPENDIX F

Land Use Data

Appendix F

Land Use Data

Land Use Categories	1971 (acres)	1985 (acres)	Average Change (acres/yr)
Crop land	272805	263301	-679
Pasture	126376	121552	-345
Forest	3264659	3136202	-9176
Non-Forested Wetland	127519	127726	15
Mining	23490	26446	211
Open Land	169575	158145	-816
Recreation	62649	66640	285
Residential	643978	771008	9074
Salt Water Wetland	46725	46609	-8
Commercial/Industrial	81724	102113	1456
Urban Open	74576	83388	629
Transportation	55807	62297	464
Waste Disposal	7750	10192	174
Water	165431	167505	148
Woody Perennial	37693	39565	134
Total*	5160757	5182689	

Source: Data Center, Massachusetts Executive Office of Environmental Affairs

Combined Land Use Categories	1971 (acres)	1985 (acres)	Average Change (acres/yr)
Crop + Pasture	399181	384853	-1023
Forest	3264659	3136202	-9176
Resid. + Comm. + Indust. + Transp.	781509	935418	10994
Wetland	174244	174335	7
Other	541164	551881	766
Total	5160757	5182689	

Source: Aggregation of figures from the previous table.

* Note that 1971 and 1985 totals differ, implying that these figures are inexact.

Combined Land Use Categories	Percent of Total Area in 1985:
Crop + Pasture	7.43%
Forest	60.51%
Wetland + Water	6.59%
Residential	14.88%
Other Developed	3.17%
Other	7.42%
Total	100.00%

Source: Re-aggregation of figures from the previous tables.

APPENDIX G

Worksheets to Calculate Projected CO_2 Emissions from Fossil & Biomass Fuels for the Year 2000

TABLE 1	Estimates of Residential Sector CO_2 Emissions for the Year 2000
TABLE 2	Estimates of Commercial Sector CO_2 Emissions for the Year 2000
TABLE 3	Estimates of Industrial Sector CO_2 Emissions for the Year 2000
TABLE 3a	Estimate of Carbon Stored by Non-Fuel Use in the Industrial Sector for the Year 2000
TABLE 4	Estimates of Transportation Sector CO_2 Emissions for the Year 2000
TABLE 5	Estimate of Total Electric Utility CO_2 Emissions for the Year 2000

Worksheets to Calculate Projected CO_2 Emissions from Fossil & Biomass Fuels for the Year 2000

Notes

Column 1 Fuel use figures are from the 1995 SAFER Forecast, using REMI's 1995 economic forecasts for the year 2000 (see Appendix A of this Inventory for further discussion). End uses within coal and oil categories are based on percentage uses reported in SEDS. Wood use is expressed in tons per year, not mmBtu's.

Column 1b Table 3a only. Fraction used for non-fuel is calculated from U.S. averages using the EIA Annual Energy Review, Table 1-15, and U.S. consumption estimates in SEDS.

Column 1c Table 3a only. = (1) x (1B).

Column 2: Coefficients are from the EPA *Workbook.* Coefficient for wood is expressed in percentage of carbon content by weight.

Column 2a Table 3a only. = (2) x (2B).

Column 2b Table 3a only. Source: the EPA *Workbook*, Table D1-3.

Column 3 = (1) x (2)/2000, except that the calculation for wood = (1) x (2).

Column 4 Table 3 only. "Stored Carbon" is calculated in Table 3a and is netted out of the calculation of carbon for the industrial sector (Table 3, Column 6).

Column 5 "International Bunker" consists of fuels used in international transportation, which is not applicable in Massachusetts.

Column 6 (6) = (3) except in Table 3, where Net Carbon = (3) - (4) - (5).

Column 7 Percentage of carbon released in combustion is from the *Workbook*, pages D-1-10).

Column 8 = (6) x (7). This is the same as (3) x (7) except in Table 3.

Column 9 = (8) x (44/12). The molecular weight of carbon = 12; of CO_2 = 44.

Wood* Wood consumption figures are given in tons, not mmBtu's, and carbon content is expressed as a percentage by weight. Wood consumption is assumed to be unchanged from 1990, absent any new projection information. Wood figures are not included in the Totals.

Bituminous Coal** Table 5 only. A portion of the electricity from coal-burning power plants located in Massachusetts also serves customers in other states. For this reason, in-state CO_2 emissions from coal are expected to be higher than the total (net) emissions from coal shown here.

System Purchases*** Table 5 only. "System Purchases" are imports whose fuel type is unknown. These are projected to total 5,426.600 MWH. NEPOOL estimates its average CO_2 for the year 2000 at 0.49 tons per MWH (*NEPOOL Generation Emissions Analysis; Summary Report*, December 1995, p. 110). Using this system wide average, DOER projects that system purchases will contribute 2,659,034 tons of CO_2 in the year 2000.

APPENDIX G
TABLE 1
Estimates of Residential Sector CO_2 Emissions for the Year 2000

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5		N/A	N/A	Same as 3	99%		
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	88,417,000	44.0	1,945,174				99%	1,925,722	7,060,982
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	1,035,000	43.5	22,511				99%	22,286	81,716
LPG	3,548,000	37.8	67,057				99%	66,387	243,418
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil		47.4							
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal	960,000	62.1	29,808				99%	29,510	108,203
Bituminous Coal	240,000	56.0	6,720				99%	6,653	24,394
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	122,700,000	31.9	1,957,065				99.5%	1,947,280	7,140,025
Wood*	220,000	47.5%	104,500				90%	94,050	344,850
Ethanol		41.8							
TOTAL [w/o wood]	**216,900,000**		**4,028,335**					**3,997,837**	**14,658,737**

Source: DOER SAFER Model

APPENDIX G
TABLE 2
Estimates of Commercial Sector CO_2 Emissions for the Year 2000

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5				Same as 3	99%		
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	48,775,000	44.0	1,073,050				99%	1,062,320	3,895,172
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	793,000	43.5	17,248				99%	17,075	62,609
LPG	1,190,000	37.8	22,491				99%	22,266	81,642
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline	397,000	42.8	8,496				99%	8,411	30,840
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	21,546,000	47.4	510,640				99%	505,534	1,853,624
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal	550,000	62.1	17,078				99%	16,907	61,991
Bituminous Coal	550,000	56.0	15,400				99%	15,246	55,902
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	91,100,000	31.9	1,453,045				99.5%	1,445,780	5,301,193
Wood*		47.5%							
Ethanol		41.8							
TOTAL	**164,901,000**		**3,117,447**					**3,093,538**	**11,342,973**

Source: DOER SAFER Model

APPENDIX G
TABLE 3
Estimates of Industrial Sector CO_2 Emissions for the Year 2000

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil	10,207,000	45.5	232,209	216,000		16,009	99%	15,849	58,114
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	8,719,000	44.0	191,818	8,400		183,418	99%	181,584	665,807
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene	106,000	43.5	2,306	100		2,206	99%	2,183	8,006
LPG	1,808,000	37.8	34,171	26,400		7,771	99%	7,693	28,209
Lubricants	2,339,000	44.6	52,160	26,100		26,060	99%	25,799	94,597
Misc. Petroleum Products	14,460,000	44.7	323,181	14,200		308,981	99%	305,891	1,121,601
Motor Gasoline	957,000	42.8	20,480	0		20,480	99%	20,275	74,342
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	23,604,000	47.4	559,415	24,600		534,815	99%	529,467	1,941,378
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1					99%		
Bituminous Coal	2,000,000	56.0	56,000	300		55,700	99%	55,143	202,191
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	28,600,000	31.9	456,170	29,700		426,470	99.5%	424,338	1,555,905
Wood*		47.5%							
Ethanol		41.8							
TOTAL	**82,800,000**		**1,927,909**	**346,000**		**1,581,909**		**1,568,223**	**5,750,149**

Source: DOER SAFER Model

APPENDIX G
TABLE 3a
Estimate of Carbon Stored by Non-Fuel Use in the Industrial Sector for the Year 2000

	1 Consumption (mmBtu)	1A % Used as Non-Fuel	1B Non-Fuel Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	2A Gross Total Non-Fuel Use Carbon Stored (tons)	2B Fraction of Non-Fuel Use Stored	4 Stored Carbon (tons)
Asphalt and Road Oil	10,207,000	93.1%	9,502,717	45.5	216,187	100%	**216,187**
Aviation Gasoline				41.6			
Distillate Fuel Oil (Heating Oil)	8,719,000	4.4%	383,636	44.0	8,440	100%	**8,440**
Jet Fuel: Kerosene Type				43.5			
Jet Fuel: Naphtha Type				43.5			
Kerosene	106,000	4.4%	4,664	43.5	101	100%	**101**
LPG	1,808,000	96.4%	1,742,912	37.8	32,941	80%	**26,353**
Lubricants	2,339,000	100.0%	2,339,000	44.6	52,160	50%	**26,080**
Misc. Petroleum Products	14,460,000	4.4%	636,240	44.7	14,220	100%	**14,220**
Motor Gasoline	957,000	0.0%	0	42.8	0	n/a	**0**
Naphtha (<104° Fahrenheit)				40.0			
Naphtha (>104° Fahrenheit)				44.0			
Pentane Plus				40.2			
Petroleum Coke				61.4			
Residual Fuel Oil	23,604,000	4.4%	1,038,576	47.4	24,614	100%	**24,614**
Still Gas				38.6			
Waxes				43.7			
Anthracite Coal				62.1		75%	
Bituminous Coal	2,000,000	0.8%	16,000	56.0	448	75%	336
Sub-bituminous Coal				57.9			
Lignite Coal				58.7			
Coke							
Natural Gas	28,600,000	6.5%	1,859,000	31.9	29,651	100%	**29,651**
Wood*				47.5%			
Ethanol				41.8			
TOTAL	**92,800,000**		**17,522,745**		**378,762**		**345,982**

Source: DOER SAFER Model

APPENDIX G
TABLE 4
Estimates of Transportation Sector CO_2 Emissions for the Year 2000

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5					99%		
Aviation Gasoline	499,000	41.6	10,379			10,379	99%	10,275	37,676
Distillate Fuel Oil (Heating Oil)	57,989,000	44.0	1,275,758			1,275,758	99%	1,263,000	4,631,002
Jet Fuel: Kerosene Type	54,497,000	43.5	1,185,310			1,185,310	99%	1,173,457	4,302,674
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG	249,000	37.8	4,706			4,706	99%	4,659	17,083
Lubricants	3,367,000	44.6	75,084			75,084	99%	74,333	272,555
Misc. Petroleum Products		44.7							
Motor Gasoline	365,644,000	42.8	7,824,782			7,824,782	99%	7,746,534	28,403,957
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	2,744,000	47.4	65,033			65,033	99%	64,382	236,069
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal		56.0							
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	3,000,000	31.9	47,850			47,850	99.5%	47,611	174,573
Wood*		47.5%							
Ethanol		41.8							
TOTAL	**487,989,000**		**10,448,902**			**10,488,902**		**10,384,252**	**38,075,590**

Source: DOER SAFER Model

APPENDIX G
TABLE 5
Estimate of Total Electric Utility CO_2 Emissions for the Year 2000 -- In-State and Net Imported

	1 Consumption (mmBtu)	2 Carbon Content Coefficient (lbs C/mmBtu)	3 Total Carbon (tons)	4 Stored Carbon (tons)	5 International Bunkers (tons)	6 Net Carbon (tons)	7 % Carbon Combusted	8 Total Carbon Oxidized (tons)	9 CO_2 Emissions (tons CO_2)
Asphalt and Road Oil		45.5					99%		
Aviation Gasoline		41.6							
Distillate Fuel Oil (Heating Oil)	2,650,000	44.0	58,300			58,300	99%	57,717	211,62
Jet Fuel: Kerosene Type		43.5							
Jet Fuel: Naphtha Type		43.5							
Kerosene		43.5							
LPG		37.8							
Lubricants		44.6							
Misc. Petroleum Products		44.7							
Motor Gasoline		42.8							
Naphtha (<104° Fahrenheit)		40.0							
Naphtha (>104° Fahrenheit)		44.0							
Pentane Plus		40.2							
Petroleum Coke		61.4							
Residual Fuel Oil	135,450,000	47.4	3,210,165			3,210,165	99%	3,178,063	11,652,89
Still Gas		38.6							
Waxes		43.7							
Anthracite Coal		62.1							
Bituminous Coal**	79,963,000	56.0	2,238,986			2,238,986	99%	2,216,597	8,127,52
Sub-bituminous Coal		57.9							
Lignite Coal		58.7							
Coke									
Natural Gas	112,410,000	31.9	1,792,940			1,792,940	99.5%	1,783,975	6,541,24
Wood*		47.5%							
Ethanol		41.8							
Electric Utility Subtotal	330,473,800		7,300,391			7,300,391		7,236,352	26,533,29
System Purchases***									2,659,03
TOTAL ELECTRIC UTILITY									**29,192,32**

Source: DOER SAFER Model.